NAVAL FACILITIES ENGINEERING SERVICE CENTER
Port Hueneme, California 93043-4370

TECHNICAL REPORT
TR-2066-ENV

D/NETDP TECHNOLOGY DEMONSTRATION APPLICATION ANALYSIS REPORT FOR EX-SITU HOT AIR VAPOR EXTRACTION SYSTEM

by

Dharam Pal, Alexander P. Mathews,
Steven Fann, Phil Price, Ernest Lory, and Leslie Karr

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Strategic Environmental Research and Development Program
A Partnership to Improve the Environment

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13. ABSTRACT *(Maximum 200 words)*

This report summarizes the findings of a demonstration of the Hot Air Vapor Extraction (HAVE) technology, developed by Global Remedial Technologies, Inc. The technology demonstration was conducted under the Department of Defense Strategic Environmental Research and Development Program (SERDP) as part of the National Environmental Technology Test Site (NETTS) program. The technology demonstration was conducted at the Advanced Fuel Hydrocarbon National Test Site (HNTS), Port Hueneme, California, over a 3-month period between August 21, 1995 and November 22, 1995.

The primary objectives of the demonstration were to: (1) validate the efficacy of the HAVE technology to treat a wide range of hydrocarbons contaminated soils, (2) gather information necessary to estimate treatment costs, and (3) develop engineering guidance to allow routine application of this remediation technology DoD-wide. The demonstration consisted of two phases and five separate test runs. During the demonstration, the system performance was optimized by varying operating parameters and by changing the treatment cell configuration. The economic analysis indicated that the unit cost for the treatment of a batch of 750 cubic yards (cu. yds.) of soil is approximately $82/cu. yd. Larger volumes of soil can be treated at lower unit costs due to reductions in mobilization, site preparation, and startup costs.

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ABBREVIATIONS

ACFM	Actual Cubic Feet per Minute
BTEX	Benzene, Toluene, Ethylbenzene, and Xylenes
CAA	Clean Air Act
CBC	Naval Construction Battalion Center
CCR	California Code of Regulation
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
CO	Carbon Monoxide
cu. yd.	Cubic Yard
CWA	Clean Water Act
D/NETDP	Department of Defense National Environmental Technology Demonstration Program
D/NETTS	Department of Defense National Environmental Technology Test Site
DoD	Department of Defense
DTSC	California Environmental Protection Agency Department of Toxic Substances Control
EA	Environmental Assessment
FID	Flame Ionization Detector
^oF	Degree Fahrenheit
GC	Gas Chromatography
HAVE	Hot Air Vapor Extraction
HNTS	Hydrocarbon National Test Site
Kw	Kilowatt
LARWQCB	Regional Water Quality Control Board, Los Angeles Region
LEL	Lower Explosion Limit
mg	Milligrams
mg/kg	Milligrams per Kilogram
MSHA	Mine Safety and Health Administration
NIOSH	National Institute of Occupational Safety and Health
NOx	Nitrogen Oxide
NPDES	National Pollution Discharge Elimination System
NTL	National Test Location
O_2	Oxygen
OSHA	Occupational Safety and Health Act
POL	Petroleum, Oils, and Lubricants
POTWS	Publicly Owned Treatment Works
ppm	Parts per million
ppmv	Parts per million by volume
QA/QC	Quality Assurance/Quality Control

ABBREVIATIONS

RCRA	Resource Conservation and Recovery Act
ROC	Reactive Organic Compound
RWQCB	Regional Water Quality Control Board
SARA	Superfund Amendments and Reauthorization Act
SERDP	Strategic Environmental Research and Development Program
TLC	Thin Layer Chromatography
TPH	Total Petroleum Hydrocarbons

1.0 EXECUTIVE SUMMARY

1.1 BACKGROUND

This report summarizes the findings of a demonstration of the Hot Air Vapor Extraction (HAVE) technology, developed by Global Remedial Technologies, Inc. The technology demonstration was conducted under the Department of Defense Strategic Environmental Research and Development Program (SERDP) as part of the National Environmental Technology Test Site (NETTS) program. The technology demonstration was conducted at the Advanced Fuel Hydrocarbon National Test Site (HNTS), Port Hueneme, California, over a 3-month period between August 21, 1995 and November 22, 1995.

1.2 DEMONSTRATION DESCRIPTION

The HAVE technology is a mobile ex-situ vapor extraction process in which hot air is circulated through soils contaminated with fuel hydrocarbons such as gasoline, jet fuels, diesel, and heavy fuel oils, and the extracted contaminants are destroyed by combustion to carbon dioxide and water. Soil remediation is accomplished through heat and mass transfer that takes place between the circulating hot air and the soil being treated.

The construction of the treatment cell and operation follows the following five general steps. First, a membrane sheeting is placed on the ground or constructed pad and over a perimeter berm. Next, the contaminated soil is stockpiled on the membrane, and hot air injection and vapor extraction ducts are placed in a predetermined spatial arrangement. The constructed pile is then covered and sealed with a fabric resistant to high temperature. The injection and extraction ducts are now connected through manifolds to the HAVE system located next to the pile. Finally, the HAVE system is activated and hot air is circulated through the soil to extract the contaminants until the desired cleanup goals are achieved. Heat is conserved within the system by burning the extracted contaminants and continuously recirculating the combustion gases through the soil.

Previous experience has demonstrated that HAVE technology can remediate soils contaminated with gasoline and diesel fuels. This demonstration was primarily designed to determine an optimum HAVE system configuration and soil preparation condition, and to develop comprehensive technical and cost data for the removal of a range of petroleum hydrocarbons from diesel to heavy fuel oils from contaminated sites. The primary objectives of the demonstration were to:

- Meet a cleanup goal of 100 ppm for gasoline, 250 ppm for diesel fuels, and 1,000 ppm for heavy fuel oils in the soil.

- Optimize system performance by varying operating parameters, and by changing the treatment cell configuration.

- Quantify the total contaminant mass removed by the process.

- Gather information necessary to estimate treatment costs.

- Develop engineering guidance to allow routine application of this remediation technology.

The demonstration consisted of two phases and five separate test runs. About 2,000 cubic yards (cu. yds.) of soil were remediated during the demonstration. The contaminant type and the remediation temperature were key parameters that were varied during the five runs. Phase 1 consisted of two runs that examined HAVE system performance under low temperature conditions for the remediation of gasoline and mixed fuel contaminated soils. During Phase 2, heavy oil contaminated soil, and two mixed fuel contaminated soil piles with different moisture and clay contents were remediated at higher temperatures. Phase 2 demonstrations also evaluated modified treatment cell configurations to enhance heat and mass transfer between the soil and the injected air.

1.3 RESULTS

The HAVE system effectively removed both low and high boiling petroleum fractions from contaminated soils. Results from demonstration Run Nos. 4 and 5 indicate that the target remediation levels stated above were exceeded for gasoline, diesel fuels, and heavier fractions in the soil. In the treated soil, the gasoline fraction was not detected, and the average concentrations for diesel fuels and heavier fractions were 59 ppm and 126 ppm, respectively.

The total time elapsed for Test Nos. 4 and 5 was 628 hours, and during this period 1,003 cu. yds. of soil were processed, for a throughput rate of 1.6 cu. yds./hour.

The unit cost for the treatment of a batch of 750 cu. yds. of soil is estimated to be $82/cu. yd. Larger volumes of soil can be treated at lower unit costs due to reductions in mobilization, site preparation, and startup costs.

1.4 CONCLUSIONS

The results of the demonstration suggest the following conclusions:

- The HAVE technology was successful in remediating soils contaminated with gasoline, mixed fuel oils, and heavy fuel oils. The average removal efficiency from Run Nos. 4 and 5 for C4 to C22 hydrocarbon fraction was 98 percent, and the removal efficiency for C23 and heavier fraction was 95 percent.

- The HAVE system components are easily transported on tractor/trailer rigs. Assembly of the equipment and construction of the treatment cell was accomplished in 3 days. Dismantling and removal of equipment took about 3 days.

- Site preparations for the demonstrations were minimal since improvements were already made to the site as part of the HNTS test program. A prepared staging area or concrete pad would be suitable for treating multiple batches of soils. A graded surface with a slope of 2 percent or less and free of rocks and sharp objects may be satisfactory for the treatment of small volumes of soil. The technology requires an area about 150 by 80 feet for constructing a 750-cu. yd. treatment cell and setting up the HAVE equipment.

- Electric power consisting of 40-amp, 220-volt service must be available for most units. Alternately, an on-site mobile generator can be used to supply electric power. Natural gas or propane can be used for operating the furnace and catalytic oxidation units.

- The primary factors that affect process throughput are soil characteristics, contaminant type, contaminant concentration and distribution, and moisture content of the soil. These factors in turn affect the treatment duration.

- The HAVE technology performed well with soils containing less than about 14 percent moisture, and less than 20 percent clay. The cost estimates in this report are based on an initial total petroleum hydrocarbons (TPH) concentration of 5,000 ppm. Soils with higher TPH concentrations can be remediated by increasing the treatment period. The presence of soil clumps with hydrocarbons in the C23 to asphalt range will reduce treatment efficiency.

- Low temperature operation at 132°F to 150°F was successful in remediating gasoline contaminated soils. Higher temperatures are required for treating soils contaminated with mixed fuels.

- Average soil temperatures ranging from 310°F to 410°F were attained at the end of treatment with the modified HAVE system design. The enhanced design allowed remediation of contaminated soils to below target levels.

- This technology can be applied without any major soil pre-processing requirements.

- The HAVE system performed at an overall efficiency of 75 percent. Downtime was due to repairs to the power generator, furnace, and problems with the fabric cover for the cell. These problems were resolved toward the end, and Run 5 proceeded without any operational problems.

- The HAVE system will generate air emissions from thermal destruction of the petroleum hydrocarbons in the soil. The catalytic oxidation system and pollutant monitoring devices must be maintained in good working condition to assure compliance with regulatory requirements for air emissions. The soil, after treatment, can be used as fill dirt or disposed of in landfills.

- The cost-effectiveness of this technology increases with increasing volumes of soil treated at a given site. Multiple batches of 750 cu. yds. of soil can be treated at much lower costs due to the lower mobilization, startup, and training costs. Volumes less than 750 cu. yds. may incur somewhat higher costs.

- This technology can be readily implemented at other Department of Defense (DoD) sites. A 750-cu. yd. batch of soil containing moderate to low amounts of clay (less than 20 percent), moisture of about 12 percent or less, and TPH concentration of 5,000 ppm can be remediated over a period of about 18 days. This includes a treatment time of 12 days, and for a mobilization and demobilization time of about 6 days. Soils with higher TPH concentration can be remediated by extending the treatment duration.

1.5 RECOMMENDATIONS

The following recommendations are suggested to aid in the implementation of this technology at various DoD sites for the remediation of soils contaminated with petroleum hydrocarbons:

- Soil characterization as to contaminant type and distribution, moisture content, and clay content are important in the effective design of a remediation plan using the HAVE system. Higher remediation temperatures as used in Run No. 4 are recommended for soils containing moderate amounts clay and large amounts of C23+ petroleum fractions.

- The modified HAVE system design as used in Run No. 5 can be used for effective remediation of hydrocarbon fractions ranging from gasoline to heavy fuel oils.

- In addition to the use of thin layer chromatography (TLC), field measurement of moisture at various spatial locations is recommended as an additional tool to monitor treatment progress. The relationship between moisture content and TPH should be developed for the particular soil being treated, and used in project scheduling.

2.0 INTRODUCTION AND BACKGROUND

This report summarizes the findings of a demonstration of the HAVE technology, developed by Global Remedial Technologies, Inc. Data from previous case studies are also presented in this report, thus allowing decision makers to assess the applicability of this technology to other contaminated sites.

The technology demonstration was conducted at the Strategic Environmental Research and Development Program (SERDP) test location, Hydrocarbon National Test Site (HNTS), Port Hueneme, California, under the Department of Defense National Environmental Technology Demonstration Program (D/NETDP).

2.1 SERDP D/NETDP

The D/NETDP has sponsored the development of six National Test Locations, each with established infrastructure and well characterized contamination. HNTS was the national test location chosen for the demonstration of HAVE technology documented in this report.

SERDP was established by Congress to improve cooperation among Department of Defense (DoD) interservices and the U.S. Environmental Protection Agency (EPA), and to enhance resource utilization effectiveness in developing technologies for cleanup of contaminated military sites. Funded by SERDP, the D/NETDP was established to facilitate the demonstration, evaluation, and transfer of cost-effective and innovative environmental technologies from research and development stages to commercial use. Within this program, each service has focused areas for research, development, and demonstration: the Army has the responsibility for projects related to energetics and heavy metals contamination; the Navy is responsible for petroleum, oils, and lubricants (POL) contamination; and the Air Force is responsible for solvents contamination. In addition, the EPA has focused on in-situ bioremediation of organic contaminants.

The goal of SERDP's D/NETDP is to identify and establish test locations at federal facilities for hosting government and private organizations to rigorously test and evaluate new environmental control and remediation technologies. The test program at each location will be designed to obtain realistic environmental and economic information which may be extrapolated on a nationwide basis to support the adoption and use of the more cost-effective and high-performance technologies.

Test facilities have been constructed at six locations across the United States (they are called National Test Locations) to provide a consistent and uniform environment for comparing and evaluating promising cleanup and monitoring technologies

2.2 TECHNOLOGY OBJECTIVES

The demonstration was designed to meet the following objectives:

- Meet a cleanup goal of 100 mg/kg for gasoline fraction (C4 to C8), 250 mg/kg for diesel fraction (C8 to C22), and 1,000 mg/kg for heavy oil constituents (C23+) in the soil.
- Optimize the system performance by varying the spatial configuration of the injection pipes.
- Quantify performance in terms of contaminant removal efficiency and the total mass of contaminants removed by the process.
- Gather information necessary to estimate treatment costs.
- Develop engineering guidance to allow routine application of this remediation technology.

2.3 TECHNOLOGY OVERVIEW

The HAVE technology is a mobile ex-situ vapor extraction process wherein soils contaminated with fuel hydrocarbons, such as gasoline, jet fuels, diesel, and heavy fuel oils are remediated by circulating hot air through a constructed soil pile. The remediation process is accomplished through heat and mass transfer that takes place between the circulating hot air and the soil being treated. The fuel hydrocarbon vapors that are mobilized by the hot air are burnt in a combustion chamber and the combustion exhaust air is in part recirculated through the soil pile to conserve energy. The full-scale treatment process involves the following five general steps. First, a 10-mil membrane sheeting is placed on the ground and over a perimeter berm. Second, the contaminated soil is stockpiled on the membrane, and hot air injection and vapor extraction ducts are placed according to a predetermined spatial grid arrangement during the construction of the pile. Third, the constructed pile is covered and sealed with a temperature resistant fabric sheet, such as acrylic fiberglass. Fourth, the injection and extraction ducts are connected to the HAVE system located next to the pile. Fifth, the HAVE system is activated and is operated until the desired cleanup goals are achieved.

Previous experience has demonstrated that HAVE technology can remove gasoline and diesel fuel from soils. This demonstration was primarily designed to validate the efficacy of the system to remove mixed fuel hydrocarbons ranging from diesel fuel to motor oil.

2.4 DEMONSTRATION SCOPE

The scope of this demonstration included full-scale remediation of hydrocarbon fuel contaminated soils using the HAVE technology. Demonstration was conducted on the following five different treatment test cells:

Treatment Test Cell	Contamination
1	Gasoline (160 ppm maximum)
2	Mixed fuels containing diesel and heavier fractions (8,537 ppm)
3	Predominantly lubricating and heavier oil fractions (177 ppm)
4	Mixed fuels (reconstruction of treatment Cell No. 2) (5,500 ppm)
5	Mixed fuels (similar to treatment Cell No. 2) (4,700 ppm)

All test runs were conducted using the HAVE System Model SM-150. However, treatment Cell Nos. 1 and 2 were tested using the original HAVE System configuration, whereas Cell Nos. 3, 4, and 5 were tested using the modified HAVE System configuration with enhanced conduction heat transfer.

2.5 DOCUMENT ORGANIZATION

This reporting format is similar to the EPA's Site Program Application Analysis Report. Sections described below which are marked with an asterisk have been added to the EPA's format to provide additional background information, recommendations for future improvements, and conclusions.

- Section 1 — EXECUTIVE SUMMARY, summarizes the demonstration results and conclusions
- Section 2 — INTRODUCTION, concentrates on the demonstration objectives and scope
- *Section 3 — SITE DESCRIPTION, provides detailed site characterization data
- *Section 4 — DEMONSTRATION DESCRIPTION, describes the technology, installation and operation as well as the sampling strategy used to characterize the relative success of the demonstration
- Section 5 — TECHNOLOGY PERFORMANCE EVALUATION, details the numeric success of the demonstration with regard to remediation effectiveness and system performance
- *Section 6 — OTHER TECHNOLOGY ISSUES, including regulatory, health and safety, and community acceptance issues
- Section 7 — COST EVALUATION, describes the cost per unit volume remediated

- *Section 8 — RECOMMENDATIONS, describes possible process improvements for future applications
- Section 9 — CONCLUSIONS, describes the applicability of the technology to other sites, cost issues, and technology limitations

3.0 SITE DESCRIPTION

This section presents background information about the test site with respect to the HAVE technology demonstration for thermal remediation of contaminated soils. The information presented here includes site geology, hydrogeology, and the contaminant distribution in the soils tested.

3.1 LOCATION AND SETTING

The Construction Battalion Center (CBC) located at Port Hueneme, California has been selected as a Navy National Test Location for the demonstration of advanced technologies for the remediation of soils contaminated with fuel hydrocarbons. Petroleum-contaminated soils are generated at CBC during the removal of underground storage tanks (USTs). Soils contaminated with gasoline and diesel fuel have been stockpiled in a contaminated soil staging area (CSSA) at CBC for use in field-scale demonstration studies. In addition, fuel-contaminated soils from other Navy facilities are brought in to provide a varied contaminant matrix for evaluation of specific remediation technologies. The location of the staging area and the HAVE demonstration unit are shown in Figure 3.1.

Soils used in HAVE technology demonstration studies included gasoline-contaminated soils from the test site, and soils contaminated with diesel and heavier petroleum fractions imported from the Naval Weapons Station, Seal Beach.

3.2 SOIL CONTAMINANT DISTRIBUTION

Test No. 1

The gasoline soil pile used in Test No. 1 was from soils excavated during the removal of USTs at CBC Port Hueneme. The soil was stockpiled in the staging area and covered with membrane sheeting prior to the beginning of the HAVE system tests. This soil was 72 percent sand, 20 percent silt, and 7 percent clay, and contained a maximum gasoline concentration of 160 ppm. The average moisture content of the soil was 10.7 percent.

Test No. 2

The soils used in Test No. 2 were brought in by trucks from the Naval Weapons Station, Seal Beach . The soils were contaminated with mixed fuels which included hydrocarbons ranging from diesel fuel, fuel oil, heavy oil, lubricating oil, and heavier oil fractions. The soils were 57 percent sand, 24 percent silt, and 19 percent clay and contained an average TPH concentration of 8,537 mg/kg. The average moisture conent of the soils was 11.5 percent.

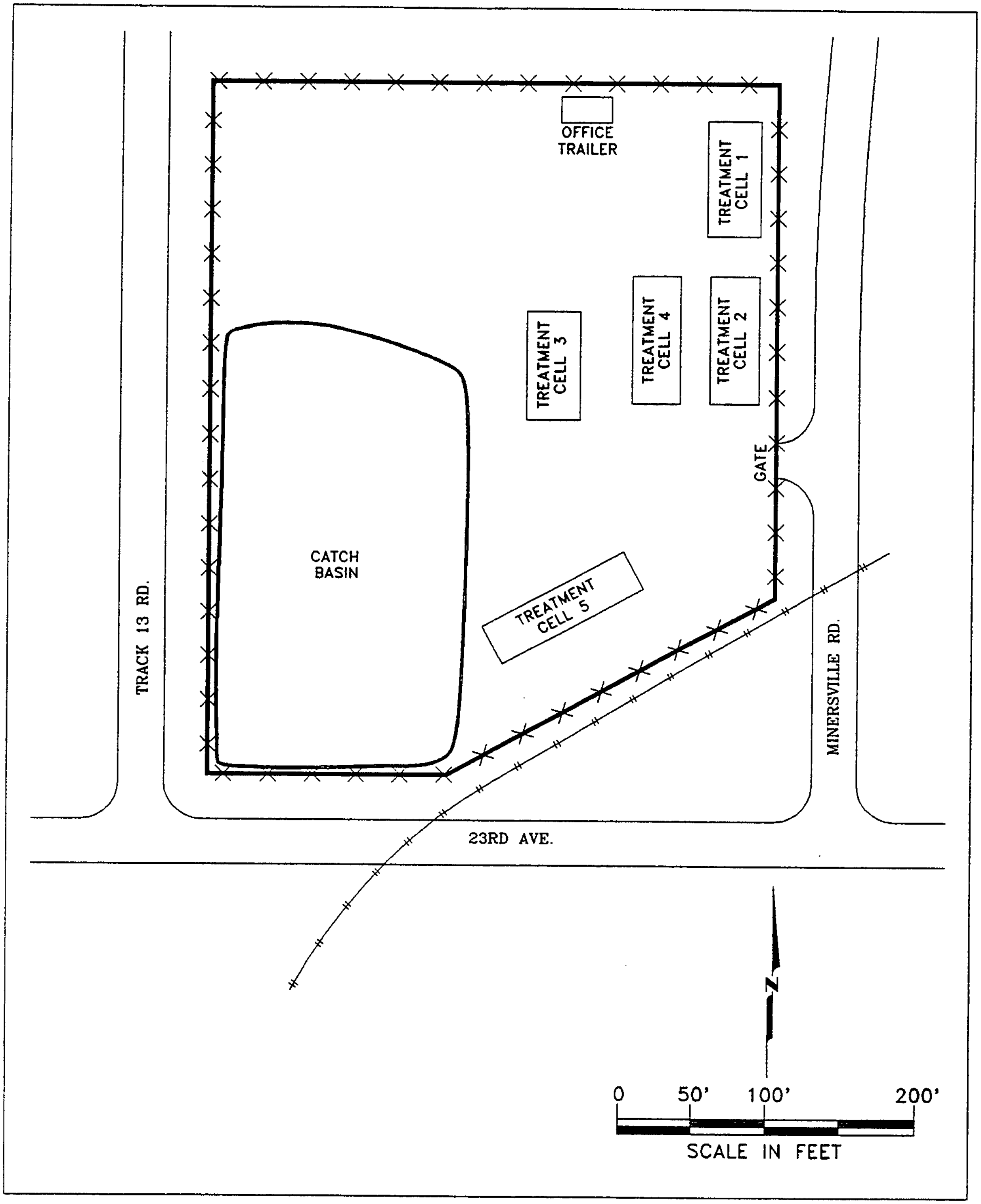


Figure 3-1. Contaminated Soil Staging Area
Navy National Test Site
NCBC, Port Hueneme

Test No. 3

Similar to Test No. 1, soils for Test No. 3 were also obtained from the excavation during the removal of USTs at CBC Port Hueneme. The soils used in Test No. 3 contained predominantly heavy oil, lubricating oil, and higher fractions, with an average TPH concentration of 177 ppm. The soil type was very similar to that of Test No. 2 and the average moisture content was 8 percent.

Test No. 4

Test No. 4 utilized the same soil from Test No. 2 after partial removal of the petroleum hydrocarbons during the 2-week operation of that test. The average TPH concentration was 5,500 mg/kg and the moisture content was 4.4 percent at the end of Test No. 2.

Test No. 5

The soils used for Test No. 5 were brought in from the Naval Weapons Station, Seal Beach, and were excavated from the same site as the soils used for Test No. 2. The soils were contaminated with mixed fuels ranging from diesel to lubricating oil and heavier fractions. The average TPH concentration was 4,700 ppm and the moisture content was 11.5 percent.

Table 3-1 provides a summary of soil contaminant distributions and soil characteristics for the soils used in this study.

The soil for Test No. 2 had high clay and moisture contents, whereas, the soil used in Test No. 5 had low clay content and high moisture content. The soil used in Test No. 4 had high clay and low moisture contents. The varied contaminant compositions and soil characteristics provide a range of conditions for testing the efficacy of the HAVE system in meeting regulatory constraints.

Table 3.1. Soil Contaminant Concentrations

Description	Test No. 1 Gasoline	Test No. 2 Mixed Fuel	Test No. 3 Heavy Oil	Test No. 4 Mixed Fuel	Test No. 5 Mixed Fuel
Average TPH Concentrations	160 ppm (peak)	8,537 ppm	177 ppm	5,807 ppm	4,705 ppm
Contaminants					
Gasoline	100%	1%	13%	1%	4%
Diesel		57%	14%	32%	23%
Fuel Oil		22%	16%	21%	20%
Heavy Oil		18%	38%	38%	35%
Lube Oil and Heavier		2%	19%	8%	18%
Average Moisture Content	10.7%	11.5%	8.0%	4.4%	11.5%
Soil Type					
Sand	72%	57%	60%	57%	54%
Silt	21%	24%	25%	24%	42%
Clay	7%	19%	15%	19%	3%

4.0 DEMONSTRATION DESCRIPTION

This section describes how the treatment system works, the steps involved in treatment system installation including the monitoring systems used to assess the demonstration progress, the various phases of the demonstration including the different kinds of runs which were made, and the sampling strategy used to measure technology performance.

4.1 TECHNOLOGY PRINCIPLES

The HAVE system is an aboveground vapor extraction system using hot air injection to enhance the removal of contaminants from a constructed soil pile. The main principles that the HAVE system relies upon are low temperature thermal desorption and soil vapor extraction to remove contaminants from the soil, and a combination of combustion and catalytic oxidation to destroy the contaminants. Thermal desorption involves the transfer of contaminants from the solid matrix of the soil as well as from the pore fluid to the soil vapor phase. Interphase heat transfer occurs from the circulating hot air to the soil by conduction and convection. This enhances the mass transfer of moisture and contaminants to the vapor phase. The released contaminant vapors are removed from the pile through vapor extraction ducts back into the burner.

4.1.1 Technology Description

The HAVE system is transportable for on-site remediation of hydrocarbon contaminants in soils, including gasoline, diesel, jet fuels, and heavy oils. As with other ex-situ remediation technologies, the contaminated soil needs to be excavated prior to treatment. The excavated soil is then built into a pile containing the hot air injection and vapor extraction ducts for circulating hot air into the pile. The soil pile is covered and sealed with a sheet of structurally strong and high temperature resistant fabric.

Once the construction of the soil pile is completed, the hot air injection and vapor extraction manifolds are connected to the HAVE system which is mounted on a trailer. The main components of the HAVE system include: a burn chamber, a vapor blower, a hot air blower, a bank of catalytic oxidizers, and control panels for displaying and recording various monitoring parameters.

The burner is fueled by propane or natural gas to heat the air. The hot air generated by the burner is fed into the soil pile through the distribution ducts to volatilize the contaminants, which are then removed from the pile through the extraction ducts and fed back into the burner. The hydrocarbon vapors thus removed from the pile are destroyed in the burner through the combustion processes. Due to the heating values of the hydrocarbons, the contaminants in the vapor become secondary fuel for the combustion in the burner, which reduces the amount of propane or natural gas needed by the burner. The temperature within the burner is around 1,800°F.

The residence time of the burn chamber as indicated by the manufacturer exceeds 0.7 seconds and sufficient turbulence for mixing is provided by using specially designed stainless steel grills and baffles within the burn chamber. The burner design is such that the vapor is retained long enough to assure a complete destruction of the contaminants. The cleaned hot air is then fed back into the soil pile to continue the cycle. As the process progresses, the oxygen available to the burner for combustion is depleted, and therefore, fresh air is drawn into the burner to supply the makeup oxygen necessary for complete combustion. Under steady state operating conditions, approximately 15 percent of the circulating air is vented through a bank of catalytic converters which remove any residual contaminants prior to release into the atmosphere.

Air monitoring instruments equipped with the HAVE system include: dual channel Gas Chromatograph Flame Ionization Detector (FID) for the monitoring of reactive organic compounds (ROCs) and PhD2 for the monitoring of carbon monoxide (CO), nitrogen oxides (NOx), oxygen (O_2), and combustible gases as percent of the lower explosive limit (LEL). ROCs were monitored at the atmospheric exhaust, furnace exhaust, and the extracted vapor from the soil pile. CO and NOx were monitored at the atmospheric and furnace exhausts. Combustible gases and oxygen were monitored at the furnace inlet and exhaust.

The HAVE system remediates soil principally by heat and mass transfer as the hot air travels through the soil pile. The hot air injection temperature and soil characteristics such as clay content, moisture, air permeability, and the type of soil contaminants are some of the important variables affecting the operation of the system. If the soil air permeability is low due to high moisture content, short circuiting may occur in the hot air path from the injection to extraction ducts. Conductive heat transfer from the injection pipe to the soil is beneficial in boiling the moisture off and stripping the contaminants along with it. The process flow schematic of the HAVE system is shown in Figure 4-1. The schematic outlines various components of the HAVE system and their interconnections during field deployment.

4.1.2 HAVE System Configurations

A key feature of the HAVE process is the configuration and placement of the injection ducts within the soil pile. Two different HAVE system configurations were tested in the demonstration: the original HAVE system configuration (treatment Cell Nos. 1 and 2), and the modified HAVE system configuration with enhanced conduction (treatment Cell Nos. 3, 4, and 5). These two configurations are described below:

<u>Original HAVE System Configuration</u>

Under this configuration of the HAVE system, four hot air injection piping systems were placed within the soil pile. Each system of injection piping consists of a 12-inch-diameter

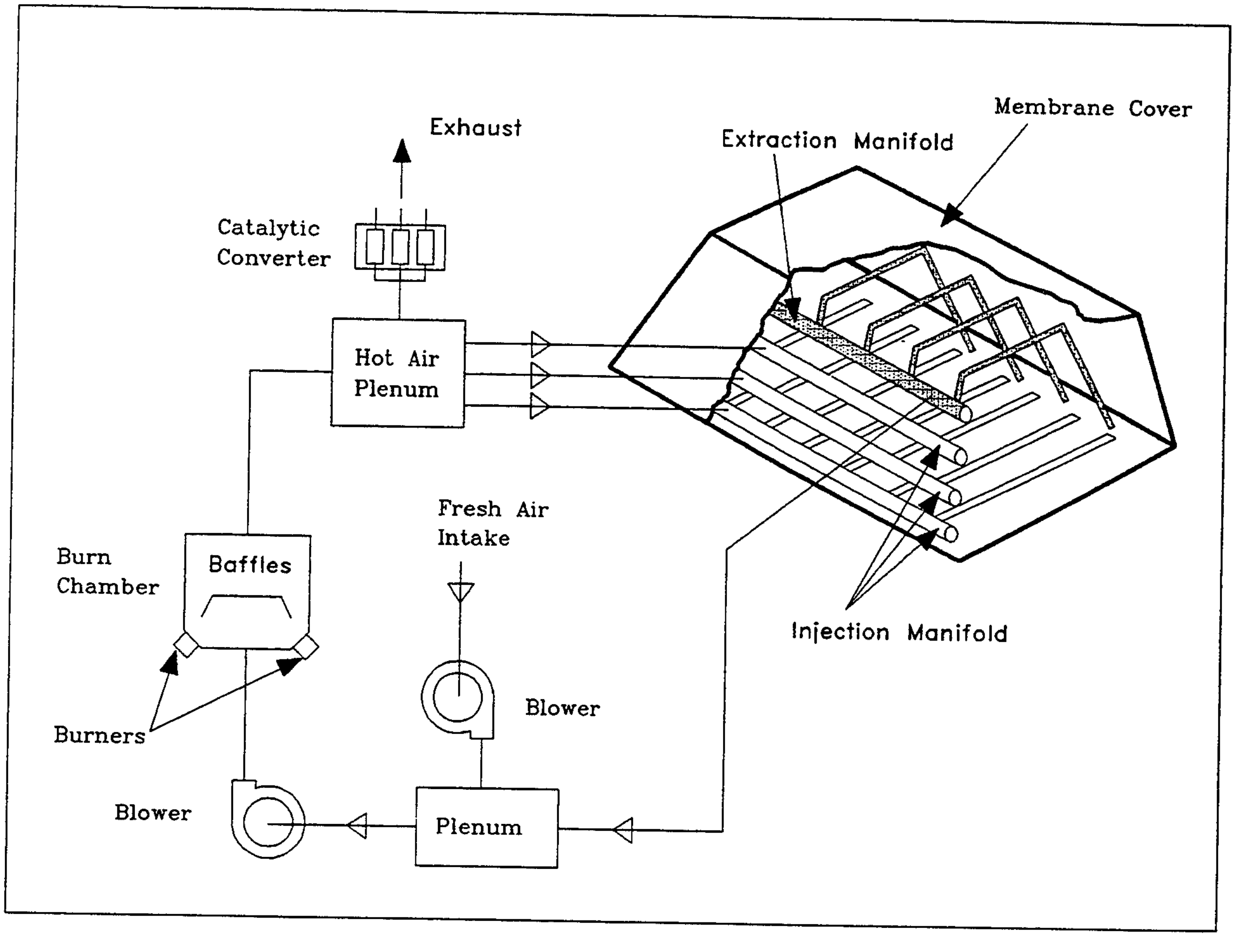


Figure 4-1. Hot Air Vapor Extraction Process Flow Diagram

distribution manifold placed along the length of the soil pile. This manifold provides hot air through a system of approximately 40 perforated 4-inch-diameter pipes connected to the manifold, placed horizontally along the width of the soil pile. The ends of the injection pipes are covered with approximately 2 feet of soil to prevent short-circuiting of hot air through the treatment cell side walls. The soil pile is then covered with a Canvex membrane fabric to avoid leakage of contaminant vapors from the pile into the atmosphere. Although the exact dimensions of the treatment cell vary depending upon the quantity of soil to be treated, typical dimensions of the treatment cell are 80 feet by 28 feet at the bottom, 65 feet by 8 feet at the top, and 12 feet high. The spacing between the consecutive injection layers of piping is about 32 inches. The upper portion of the soil pile contains a layer of 4-inch interstitial vapor collection ducts and a 12-inch main collection duct that feeds into the vapor plenum. A schematic of the original HAVE system configuration is shown in Figure 4-2.

Modified HAVE System Configuration with Enhanced Conduction

In this HAVE system configuration, the ends of the injection pipes were exposed beyond the soil treatment cell side walls, thereby allowing unrestricted hot air flow within the injection pipes. This is to increase the heat transfer from the hot air to the soil pile. Soil heating takes place primarily by conduction from the heated pipe walls into the soil as well as by contact between the hot air in the balloon and the side walls of the soil pile. Four layers of injection pipes were installed at distances of 1.5, 3, 4.5, and 6 feet from the bottom of the soil pile. A layer of 4-inch diameter vapor extraction pipes connected to a 12-inch diameter main collection manifold was placed at a distance of 8 feet from the bottom of the pile. The width of the pile is 28 feet at the bottom and about 8 feet at the top of the pile. A high temperature resistant acrylic-fiberglass membrane was used to cover and seal the soil pile to prevent the leakage of vapors into the atmosphere. This type of covering material could withstand temperatures up to 750°F, a much higher temperature than the visqueen sheeting used in the original design. This resulted in much higher soil temperatures within the pile, which were necessary to remediate soils containing significant amounts of lubricating oil and heavier petroleum fractions. A schematic of the modified HAVE system configuration is shown in Figure 4-3.

The treatment cell construction was typically completed in approximately 3 days. This included the installation of sampling probes and thermocouples within the soil pile. Typical cell dimensions and soil volumes for each level are given in the Appendix.

4.2 TREATMENT SYSTEM INSTALLATION AND OPERATION

The construction of the soil treatment cell, installation of the HAVE system, treatment operation, and post-treatment dismantling operations involved the following elements outlined below. The duration of treatment depended on the type of soil and the contaminants present.

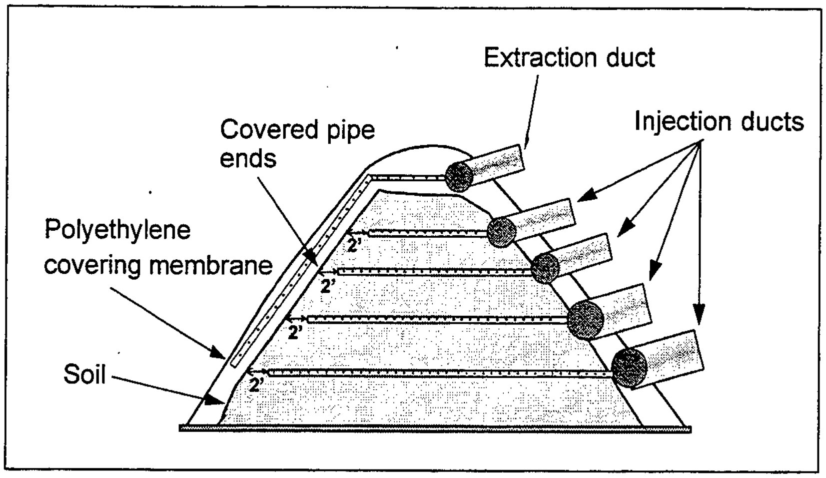


Figure 4-2. Original HAVE System Configuration

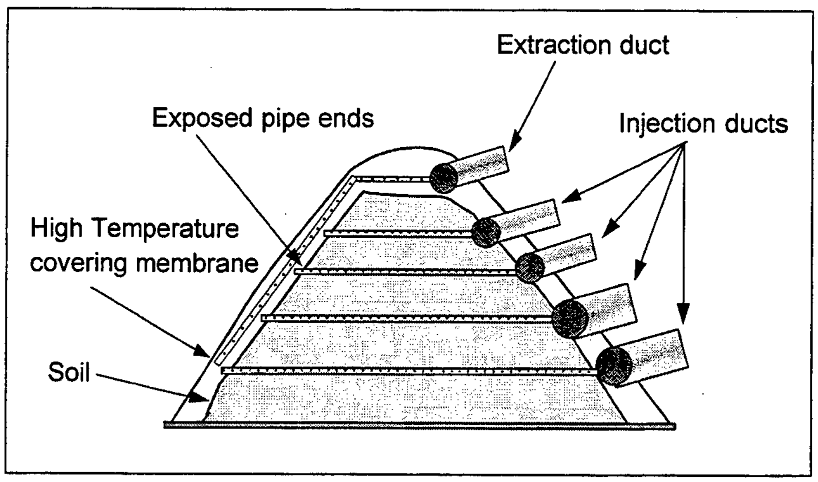


Figure 4-3. Modified HAVE System Configuration

4.2.1 Treatment System Construction

Heavy gauge membrane sheeting was placed on the ground and over a perimeter berm. The soil pile was built on the membrane to specifications, integrating the hot air injection and vapor extraction ducts. Next, the soil pile was covered with membrane fabric that can withstand high temperatures to provide a tight air seal. All duct entries were also sealed. The trailer-mounted HAVE system was pulled along the soil pile and connected to the manifold with flexible ducting. The dimensions of the treatment cell varied depending on the volume of soil treated, and are given in Table 4-1.

Construction typically followed the schedule given below for each treatment cell:

<u>Day 1 through 3</u> –

- Preparation of stockpile areas
- Transfer of soil from staging area to treatment area
- Securing of area with barriers
- Collection of pretreatment soil samples
- Delivery of propane tanks to treatment area
- Placement of HAVE system piping and manifolds within the soil pile
- Placement of monitoring probes and thermocouples
- Placement of high temperature covering over soil pile
- Positioning of HAVE system mobile unit near soil pile
- Hookup of manifolds within the pile to HAVE system
- Hookup of propane tank, electricity, and water to HAVE system

Table 4-1. Treatment Cell Dimensions

Description	Volume of Soil Treated (cu. yd.)	Base Dimension (ft)	Cell Height
Test Run No. 1 Gasoline	512	80 x 28	12ft 4in
Test Run No. 2 Mixed Fuel Oil	480	80 x 28	12ft 2in
Test Run No. 3 Heavy Oil	350	90 x 27	6ft 4in
Test Run No. 4 Mixed Fuel Oil	480	100 x 27	7ft 6in
Test Run No. 5 Mixed Fuel Oil	523	105 x 27	8ft 0in

4.2.2 Process Instrumentation and Monitoring

An extensive process monitoring program was designed and put in place to evaluate the performance of the HAVE system. Temperature sensors were embedded in the soil of each of four hot air injection levels and were evenly distributed throughout the treatment cell. The number of temperature sensor locations varied from 18 to 50, and the temperature was recorded four times per day at each location. K-type thermocouples were precisely centered between contiguous 4-inch hot air injection pipes, thus providing the lowest temperature obtainable for each soil level. To directly monitor the propagation of the thermal front, four-wire sensor arrays were prefabricated and positioned within the soil between contiguous hot air injection pipes on 3.33-inch spacing. Up to four sensor arrays were strategically placed within each treatment cell.

The air temperatures within the hot air injection pipes were monitored by placing sensors directly within the pipe air stream at points both near to the air distribution manifold and at the pipe ends. Air temperature and velocity in the main duct were monitored on an hourly basis. A pitot tube was used for air velocity measurements. Fuel consumption was monitored hourly from percent full readings on the propane tank gauge. The exhaust gases were monitored hourly for CO, NOx, O_2, and hydrocarbons. Up to 15 soil vapor samples were collected from various soil pile locations each day for all test runs, but were discontinued during Test Run No. 5 because of continued fouling of instrumentation.

4.2.3 Treatment System Operation

The treatment system operation began after a maintenance and safety check of all the components of the HAVE system. The treatment duration ranged from 3 days for Test Run No. 1 to 14.5 days for Test Run No. 4. Continuous operation, monitoring of all process parameters, and scheduled sample collections were achieved as listed below with two operators daily on 12-hour shifts:

Day 3 through 18 (variable depending on test run) –

- Collection of ten to fifteen soil samples each day through sampling ports in covering
- Collection of air permit monitoring data
- Collection of process data (monitoring of soil vapor, temperatures, and air flow rates)
- Analysis of collected soil samples using thin layer chromatography

At the end of treatment, the following operations were performed to prepare the site for the next test run:

Day 18 through 19 –

- Collection of confirmation soil samples
- Removal of soil pile covering

- Removal of HAVE system from treatment area
- Removal of pipes from soil pile by pulling pipes with special pipe collar tool outward using front end loader and/or trackhoe excavator
- Cleanup of treatment area and preparation for next soil pile

Following treatment of the last soil pile, the site was restored to its original condition and the temporary barricades were removed.

4.3 THE TWO PHASES OF THE TECHNOLOGY DEMONSTRATION

The hot air vapor extraction technology demonstration for ex-situ remediation of soils was conducted in two phases, identified as Phases 1 and 2. Phase 1 consisted of two runs with gasoline contaminated soil, and mixed fuel contaminated soil. The original HAVE system design and treatment cell configuration was used for the tests in Phase 1, and the system was operated at a low temperature due to the temperature limitations of the Canvex membrane cover. Phase 2 consisted of three runs with the modified HAVE system design that was capable of maintaining the higher soil temperatures required to volatilize the heavier petroleum hydrocarbon fractions in the soil. One run was made with heavy oil contaminated soil, and two runs were made with soils contaminated with mixed fuel oil.

The principal operating parameters and variables affecting HAVE technology performance are the soil temperature, air flow rate, contaminant type and concentration, soil type, and soil moisture content. During Phase 1, contaminant type and soil type were different for the two runs conducted at the low average soil temperature. Preferred equipment operating procedures, air flow rate, and pressure were developed during these tests.

During Phase 2, tests were run with varied contaminant type and concentration at a higher average soil temperature. Moreover, tests were done to determine the effects of augmenting soil moisture, and the effects of the addition of surfactants in enhancing or accelerating the removal of the heavier petroleum fractions ranging from heavy oil to lubricating oil.

4.4 SAMPLING STRATEGY

Sampling was conducted before treatment, during treatment, and after completion of the demonstration. For each cell, several soil samples and soil vapor samples were collected during treatment to monitor progress. In addition, the circulating hot air, the exhaust air stream, and the furnace operating parameters were monitored. Tables 4-2 to 4-6 list the number and types of samples collected and the analytical methodology used to characterize the samples. Figure 4-4 is a process stream flow diagram, and indicates the monitoring locations.

Table 4-2. Monitoring and Sampling for Cell 1, Gasoline Soil Pile

	TEST PARAMETERS	NUMBER OF SAMPLES		
		Pretreatment	Treatment	Post-Treatment
1.0	**SOIL TESTING**			
	Clay Content	4		
	Porosity (bulk density)	4		
	Particle Size Distribution	4		
	Volatile Matter Content	4		
	Soil Moisture Content	4	15/day	
	Analytical Methodology			
	8015 Modified-Fuel Finger Printing	20		
	8015 Modified-Gasoline			20
	Passive Soil Vapor Sampling	20		20
	8015 Soil Vapor Monitoring		3 samples/2 days	
	Field Screening Methods			
	Thin Layer Chromatography		none[a]	
	Flame Ionization Detector - portable		20/day for 2 days	
2.0	**PROCESS MONITORING**			
	Soil Temperature (13 sensor locations[b])		2/day	
	Air Temperature (main return duct) -on-board thermocouple -direct reading instrument		 2/day 2/day	
	Air Velocities - on-board pitot tubes		hourly	
	Air Moisture (return duct & fresh air intake) relative humidity - direct reading sensor		2/day	
	Air Pressure (soil pile)		1/day[c]	
	Fuel Consumption		hourly	
	Electricity Consumption		n/a	
3.0	**VAPOR MONITORING (exhaust & process)**			
	-CO		logged 1/hour	
	-NOx		logged 1/hour	
	-O_2		logged 1/hour	
	-Hydrocarbons		logged 1/hour	

[a] TPH concentrations below detection levels.

[b] 7 sensor failures.

[c] Instrument failure on 8/7.

Table 4-3. Monitoring and Sampling for Cell 2, Mixed Fuel Soil Pile

	TEST PARAMETERS	NUMBER OF SAMPLES		
		Pretreatment	Treatment	Post-Treatment
1.0	**SOIL TESTING**			
	Clay Content	2		
	Porosity (bulk density)	2		
	Particle Size Distribution	2		
	Volatile Matter Content	2		
	Soil Moisture Content		15/day	
	Analytical Methodology			
	8015 Modified-Fuel Finger Printing	20		
	8015 Modified-Diesel & Heavier		15/day for 12 days	20
	8015 Soil Vapor Monitoring		3/day for 8 days	
	Field Screening Methods			
	Thin Layer Chromatography		15/day for 14 days	
	Flame Ionization Detector - portable		18/day for 10 days	
2.0	**PROCESS MONITORING**			
	Soil Temperature (41 sensor locations)		4/day	
	Air Temperature (main return duct) -on-board thermocouple -direct reading instrument		 hourly n/a	
	Air Velocities - on-board pitot tubes		hourly	
	Air Moisture (return duct & fresh air intake) relative humidity-direct reading sensor		discontinued	
	Air Pressure (soil pile)		discontinued	
	Fuel Consumption		hourly	
	Electricity Consumption		n/a	
3.0	**VAPOR MONITORING (exhaust & process)**			
	-CO		hourly	
	-NOx		hourly	
	-O_2		hourly	
	-Hydrocarbons		hourly	

Table 4-4. Monitoring and Sampling for Cell 3, Heavy Oil Soil Pile

	TEST PARAMETERS	NUMBER OF SAMPLES		
		Pretreatment	Treatment	Post-Treatment
1.0	**SOIL TESTING**			
	Clay Content	2		
	Porosity (bulk density)	2		
	Particle Size Distribution	2		
	Volatile Matter Content	2		
	Soil Moisture Content		10/day	
	Analytical Methodology			
	8015 Modified-Fuel Finger Printing	20		
	8015 Modified-Diesel & Heavier		10/day for 4 days	10
	8015 Soil Vapor Monitoring		10/day for 4 days	
	Field Screening Methods			
	Thin Layer Chromatography		10/day for 6 days	
	Flame Ionization Detector - portable		10/day for 4 days	
2.0	**PROCESS MONITORING**			
	Soil Temperature (26 sensor locations)		4/day	
	Air Temperature (main return duct) -on-board thermocouple -direct reading instrument		 hourly n/a	
	Air Velocities - on-board pitot tubes		hourly	
	Fuel Consumption		hourly	
	Electricity Consumption		n/a	
3.0	**VAPOR MONITORING (exhaust & process)**			
	-CO		hourly	
	-NOx		hourly	
	-O_2		hourly	
	-Hydrocarbons		hourly	

Table 4-5. Monitoring and Sampling for Cell 4, Mixed Fuel Soil Pile

	TEST PARAMETERS	NUMBER OF SAMPLES		
		Pre-treatment	**Treatment (15 Days)**	**Post-treatment**
1.0	**SOIL TESTING**			
	Clay Content	2		
	Porosity (bulk density)	2		
	Particle Size Distribution	2		
	Volatile Matter Content	2		
	Soil Moisture Content		10/day	
	Analytical Methodology			
	8015 Modified-Fuel Finger Printing	20		
	8015 Modified-Diesel & Heavier		10/day for 13 days	10
	8015 Soil Vapor Monitoring		3/day for 10 days	
	Field Screening Methods			
	Thin Layer Chromatography		10/day for 15 days	
	Flame Ionization Detector - portable		11/day for 9 days	
2.0	**PROCESS MONITORING**			
	Soil Temperature (32 sensor locations)		4/day	
	Air Temperature (main return duct) -on-board thermocouple -direct reading instrument		 hourly n/a	
	Air Velocities - on-board pitot tubes		hourly	
	Fuel Consumption		hourly	
	Electricity Consumption		n/a	
3.0	**VAPOR MONITORING (exhaust & process)**			
	-CO		hourly	
	-NOx		hourly	
	-O_2		hourly	
	-Hydrocarbons		hourly	

Table 4-6. Monitoring and Sampling for Cell 5, Mixed Fuel Soil Pile

	TEST PARAMETERS	NUMBER OF SAMPLES		
		Pre-treatment	Treatment (11.5 Days)	Post-treatment
1.0	**SOIL TESTING**			
	Clay Content	2		
	Porosity (bulk density)	2		
	Particle Size Distribution	2		
	Volatile Matter Content	2		
	Soil Moisture Content		12/day	
	Analytical Methodology			
	8015 Modified-Fuel Finger Printing	12		
	8015 Modified-Diesel & Heavier		12/day for 11 days	12
	Passive Soil Vapor Sampling	eliminated		
	8015 Soil Vapor Monitoring		discontinued	
	Field Screening Methods			
	Thin Layer Chromatography		12/day for 12 days	
	Flame Ionization Detector - portable		discontinued	
2.0	**PROCESS MONITORING**			
	Soil Temperature (26 sensor locations)		4/day	
	Air Temperature (main return duct) -on-board thermocouple -direct reading instrument		 hourly n/a	
	Air Velocities - on-board pitot tubes		hourly	
	Fuel Consumption		hourly	
	Electricity Consumption		n/a	
3.0	**VAPOR MONITORING (exhaust & process)**			
	-CO		hourly	
	-NOx		hourly	
	-O_2		hourly	
	-Hydrocarbons		hourly	

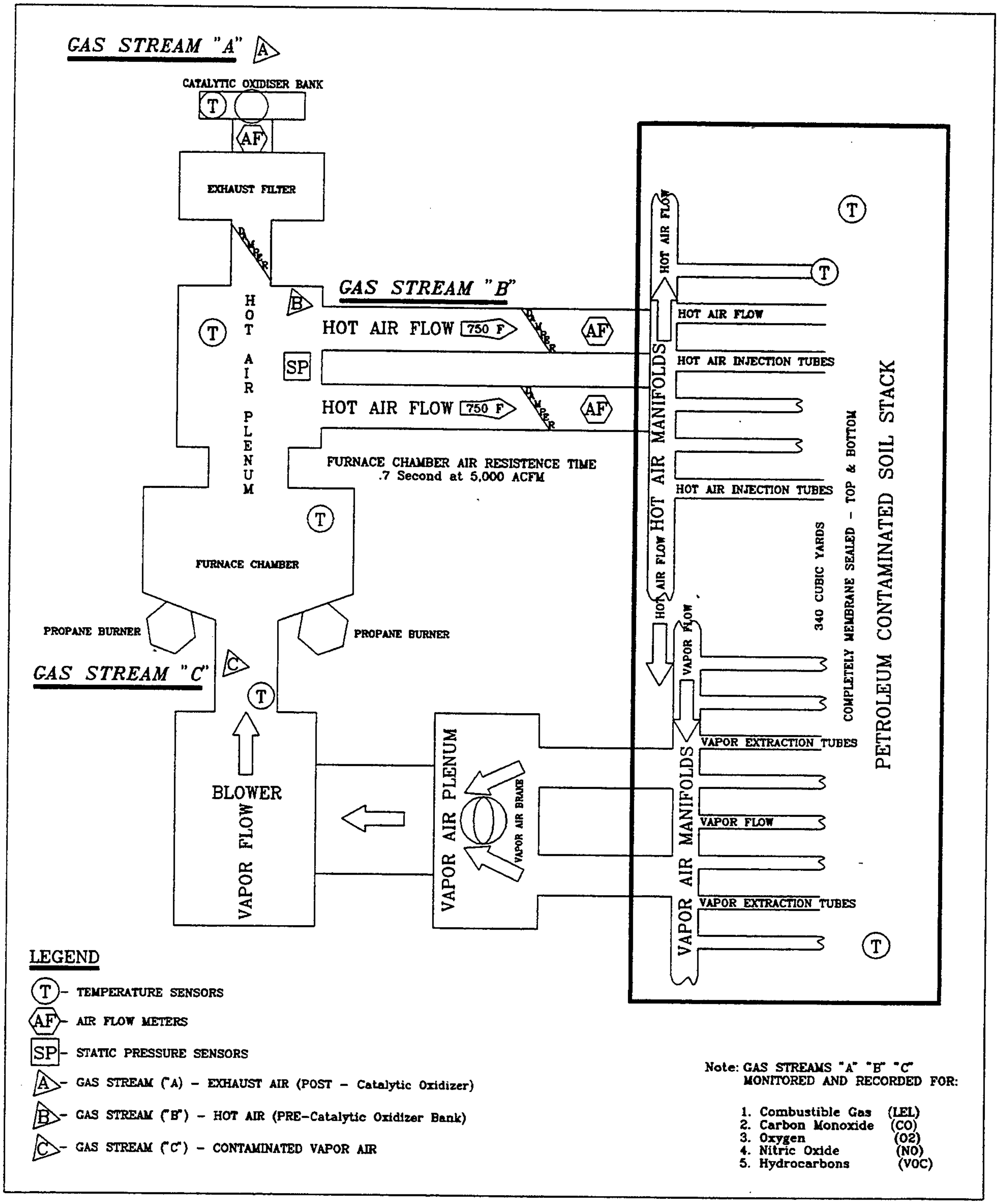


Figure 4-4. Process Stream Flow Diagram

4.4.1 Soil Sampling

An extensive soil sampling program was designed to evaluate the performance of the HAVE system. A network of sampling locations was established on a three-dimensional grid to obtain representative soil samples for analysis. The number of soil samples collected ranged from 10 to 15 per day for the duration of the test runs. Similar soil collection protocols were used throughout the demonstration program. Soil samples were collected following the guidelines provided in: (1) SW 846 Test Methods for Evaluating Solid Waste, EPA 1986, and (2) ER 1110-1-263, Appendix F, Sample Handling Protocol for Low, Medium, and High Concentration Samples of Hazardous Waste, October 1990.

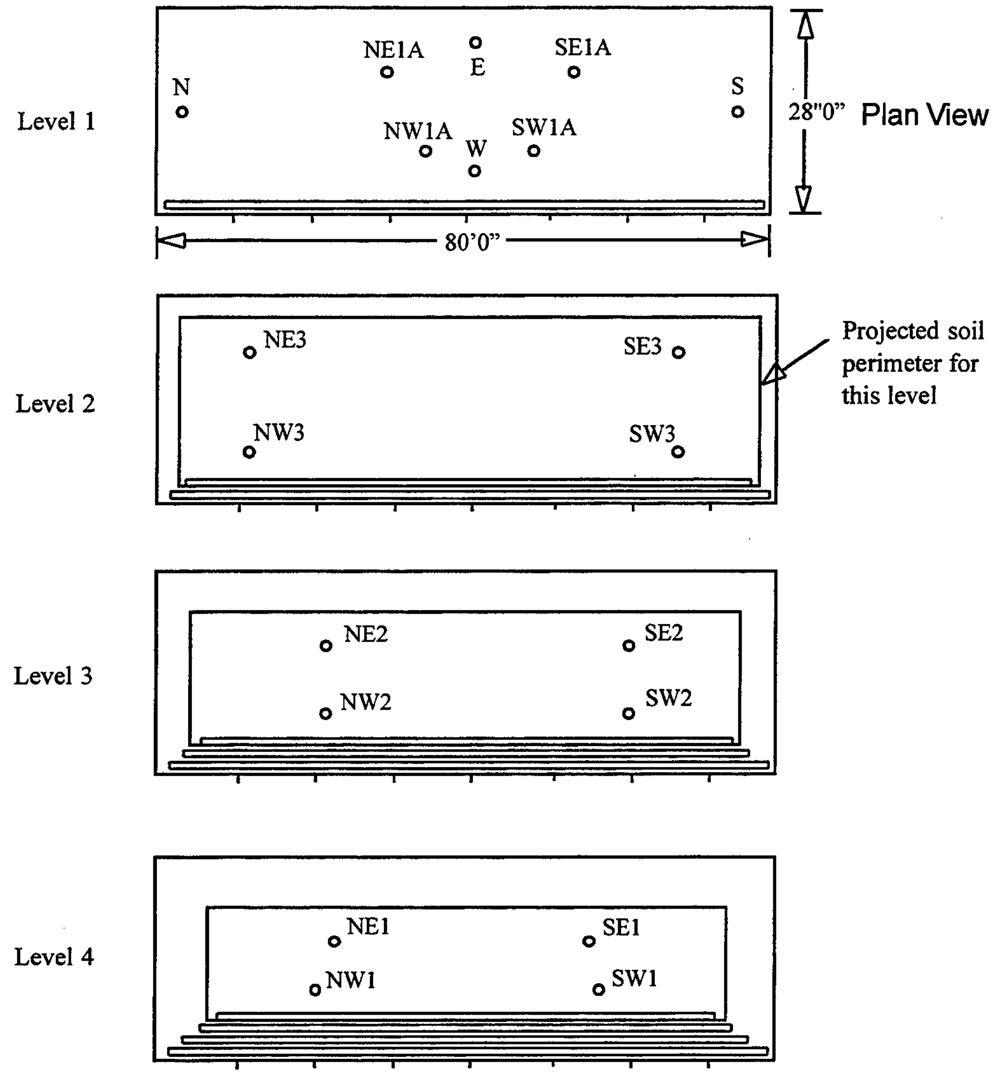
Treatment progress for each portion of the treatment cell was tracked through soil sampling through ports that were prefabricated into the membrane fabric. Each sample was collected by inserting a push sampler through each port without shutting down the HAVE system. The push sampler was 10 feet in length and 3/4 inch in diameter. The sampling locations were predetermined and spatially arranged to obtain representative data from each of the levels within the treatment cell. Figures 4-5 through 4-9 show the sampling plan design for Cells 1 through 5, respectively.

The typical collection method for retrieving soil from Level 1 was as follows. The sampler was first pushed 4 feet into the pile, and the sample collected was discarded. The sampler was then reintroduced into the same bore hole and pushed in from 4 feet to 8 feet into the pile, and the collected sample was split and placed in appropriate sample containers. Field screening samples were placed in a zip-lock freezer bag and laboratory samples were placed in a glass jar. The containers were secured tightly and placed in a cooler for transport to the laboratory. Sample information was recorded in the field notebook and the chain of custody documents were completed.

4.4.2 Soil Vapor Sampling

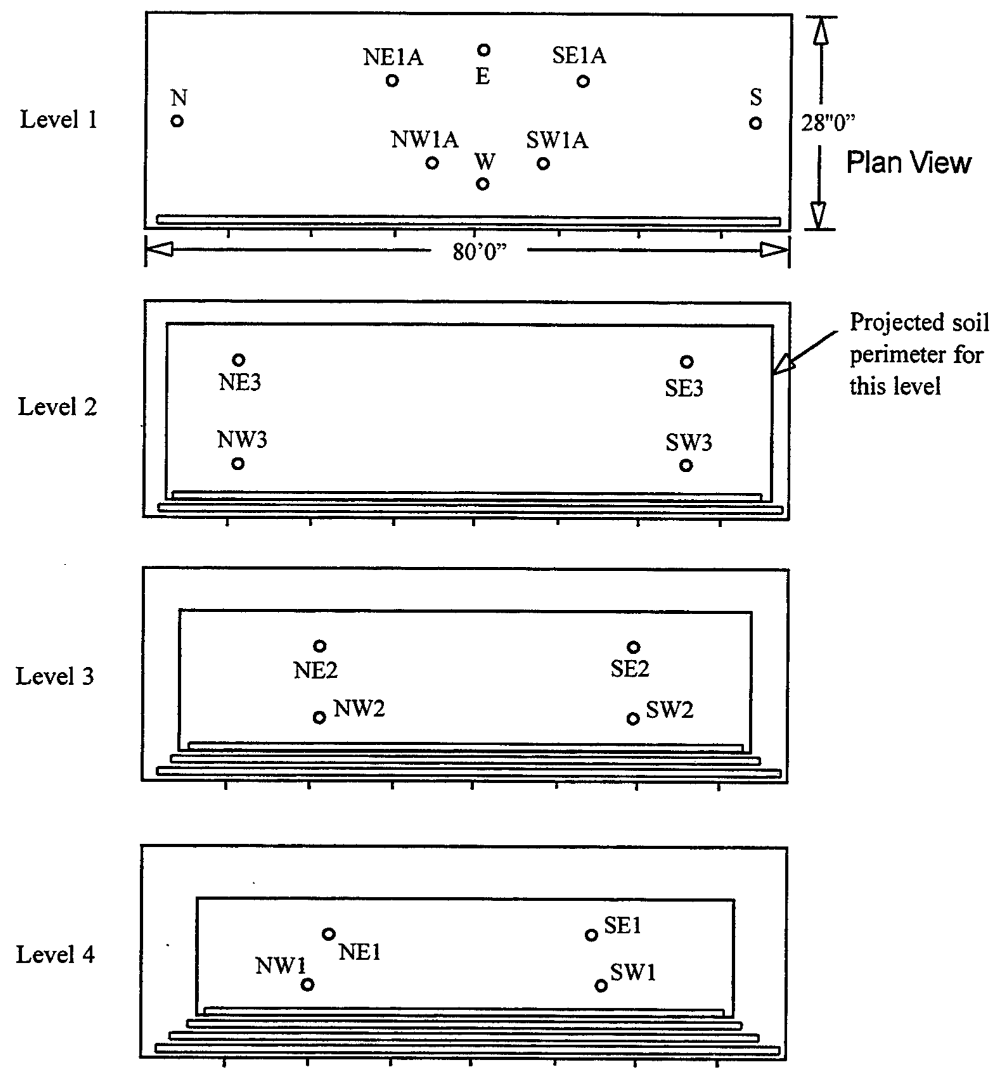
Soil vapors from up to 20 points within treatment Cells 1 to 4 were monitored each day. Soil vapor monitoring probes were placed at regular and evenly spaced intervals as shown in Figures 4-10 and 4-11 for treatment Cells 3 and 4. The probes were sufficiently removed from the soil sample collection areas to protect them from damage by soil sampling tools. A Foxboro Century Model 128 Portable Organic Vapor Analyzer (FID) calibrated to a hexane standard was used to analyze the vapor samples.

Soil vapor screening for each port consisted of three steps, namely, sample purge, equilibration, and sample analysis. The vapor extraction port was purged using an explosion-proof portable pump by drawing approximately 5 liters of vapor. The pump was then disconnected from the line and the line was capped for approximately 30 seconds to permit the air pressure to equilibrate. Following equilibration, the FID was connected to the line and the organic vapor reading was immediately logged.



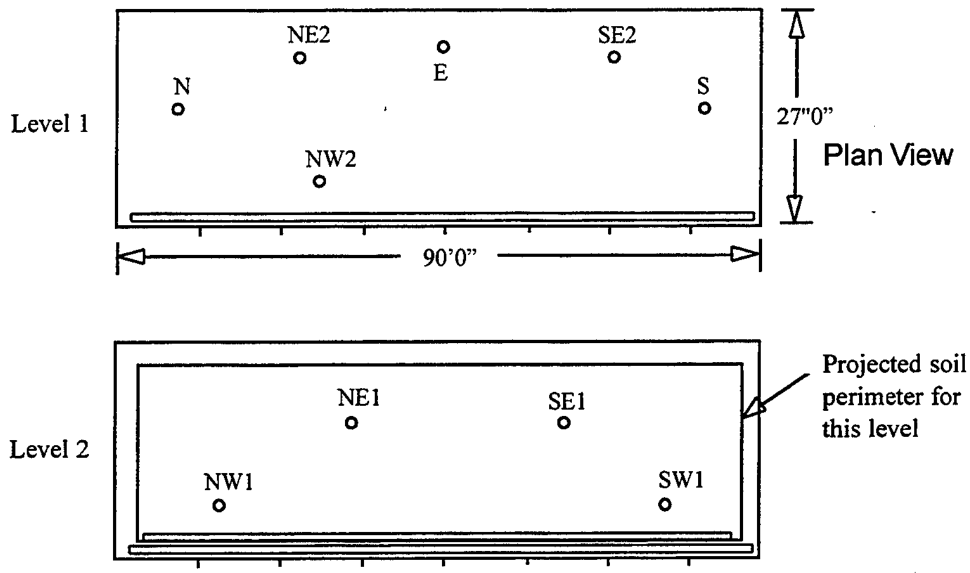
Note: Soil samples were collected between each injection level at depths ranging from 4 to 7 feet below soil surface.

Figure 4-5. Sampling Plan Design for Cell No. 1



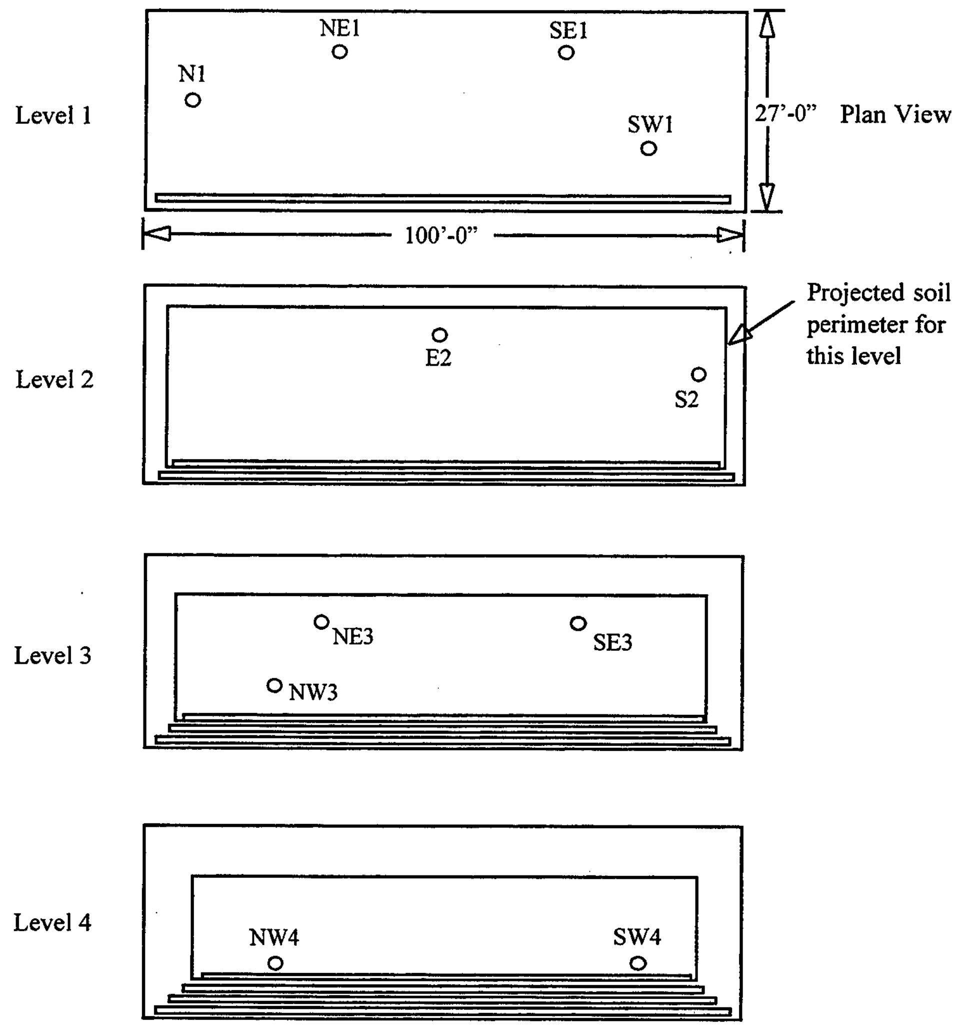
<u>Note</u>: Soil samples were collected between each injection level at depths ranging from 4 to 7 feet below soil surface.

Figure 4-6. Sampling Plan Design for Cell No. 2



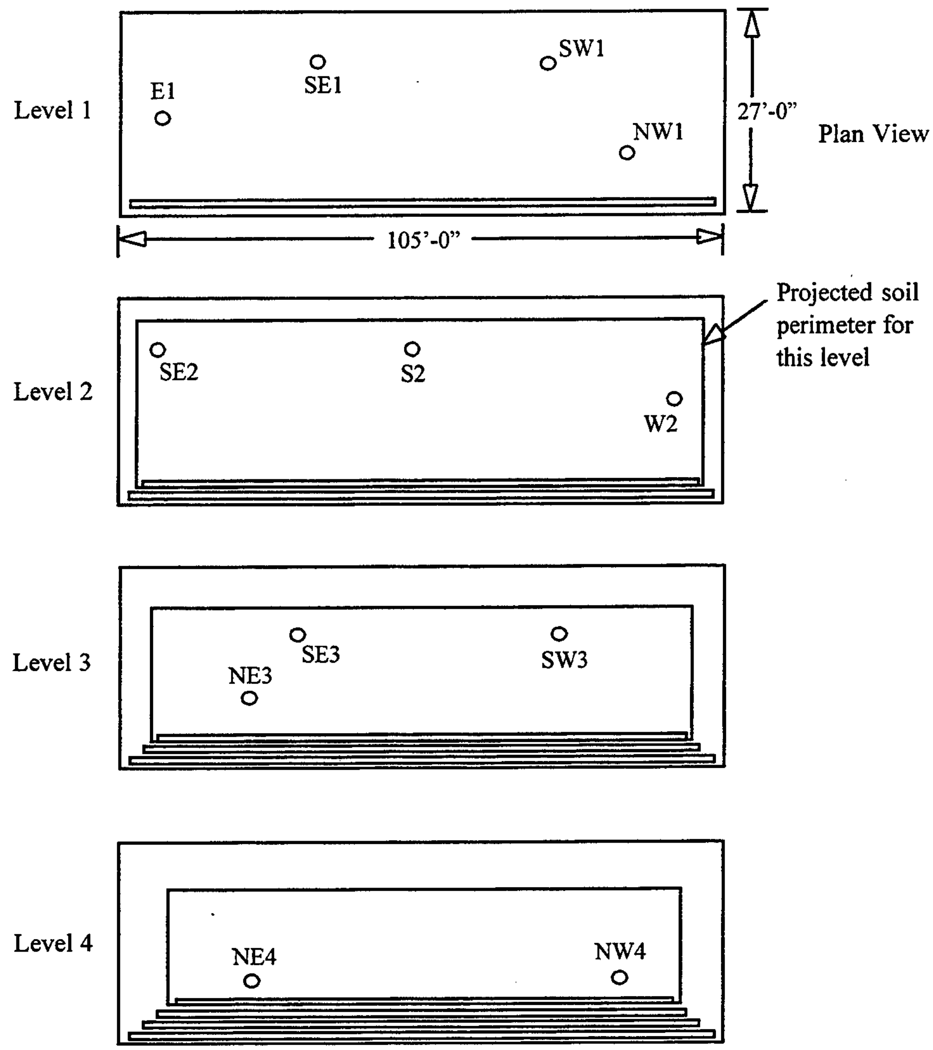
Note: Soil samples were collected between each injection level at depths ranging from 4 to 7 feet below soil surface.

Figure 4-7. Sampling Plan Design for Cell No. 3



Note: Soil samples were collected between each injection level at depths ranging from 4 to 7 feet below soil surface.

Figure 4-8. Sampling Plan Design for Cell No. 4



Note: Soil samples were collected between each injection level at depths ranging from 4 to 7 feet below soil surface.

Figure 4-9. Sampling Plan Design for Cell No. 5

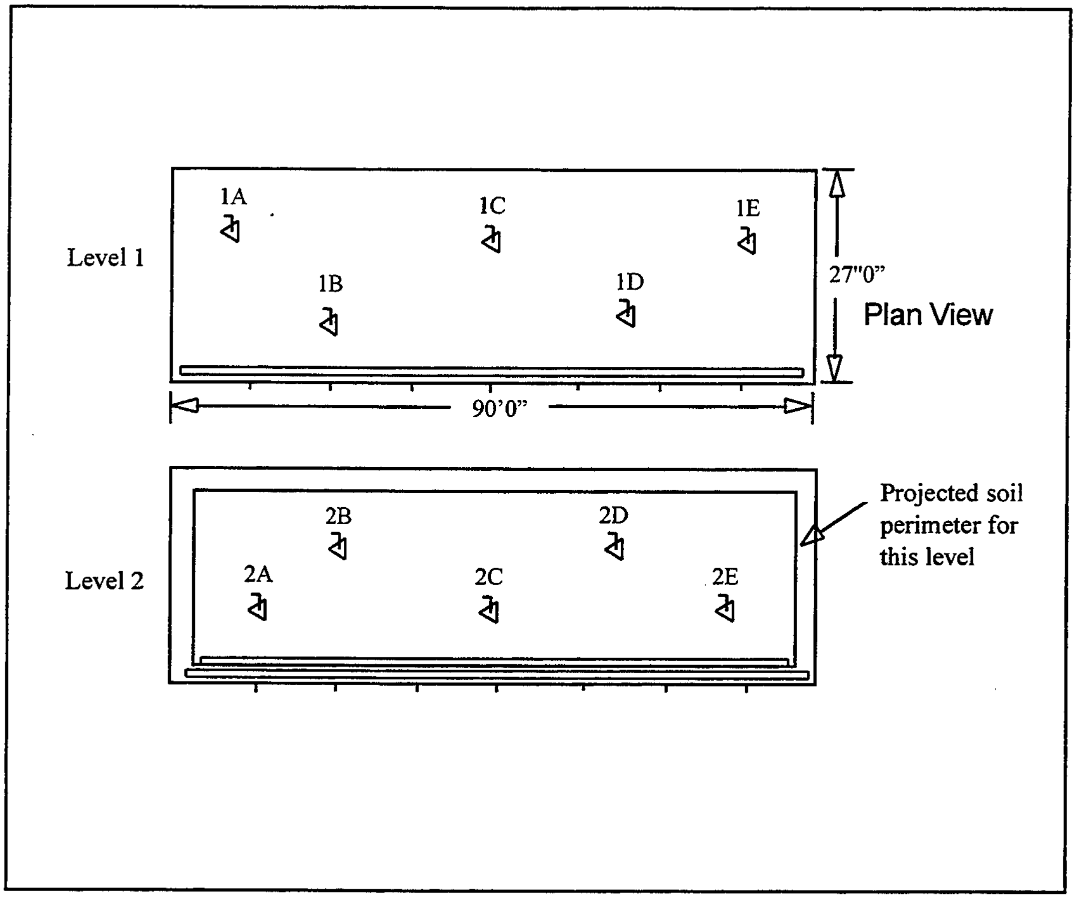


Figure 4-10. Soil Vapor Monitoring Locations for Cell No. 3

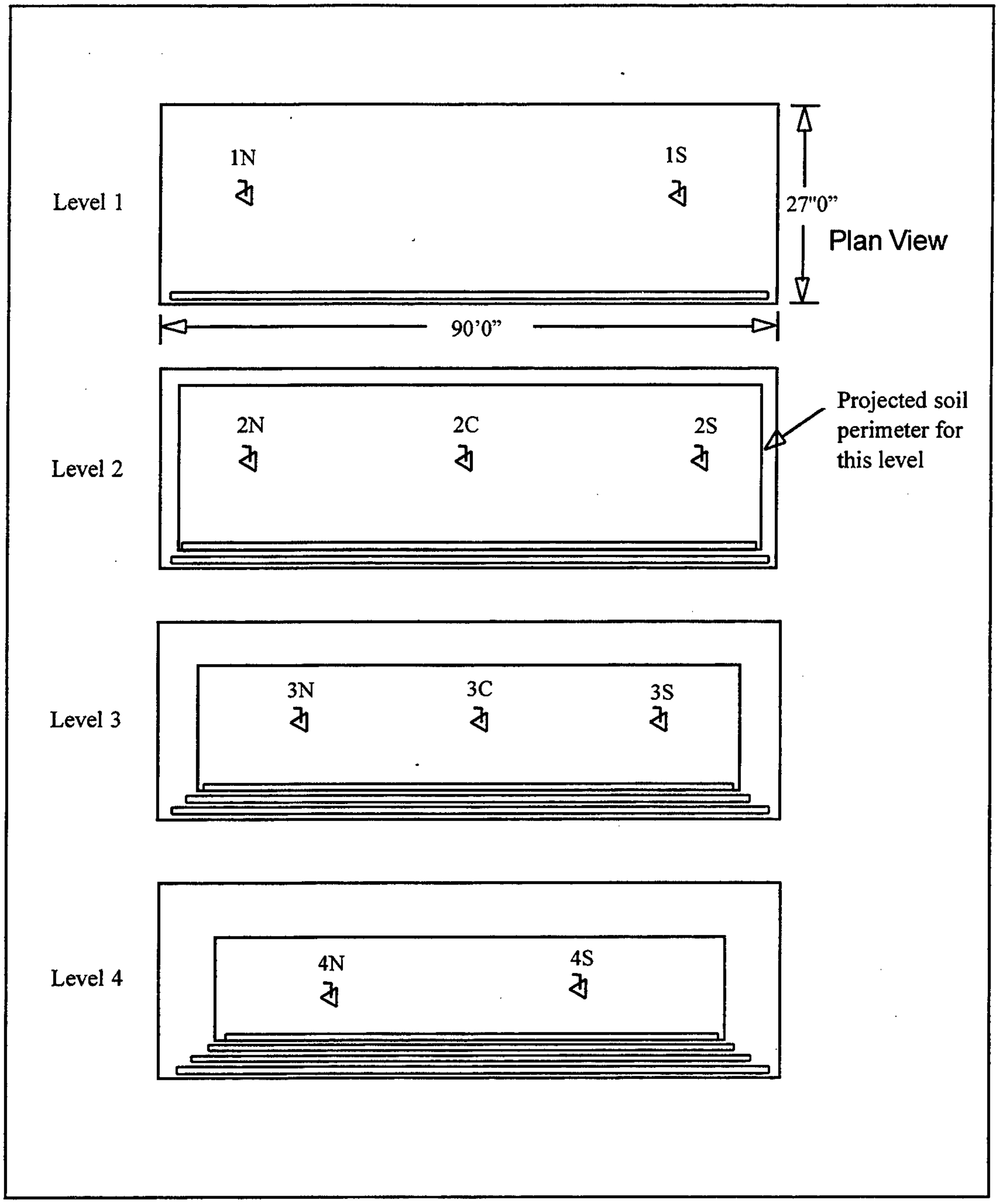


Figure 4-11. Soil Vapor Monitoring Locations for Cell No. 4

The vapor monitoring data were found to be unreliable due to broad oscillations of instrument readings and FID flame-out during treatment of heavy hydrocarbons. Moreover, the data showed no observable trends as treatment progressed, and there was no correlation between the FID data and the analytical data from soil samples sent to the laboratory. Hence, direct vapor monitoring was eliminated during Test Run 5.

4.4.3 Soil Temperature Monitoring

Soil temperature was monitored, as discussed previously, throughout the treatment duration at several locations within the cell. Figures 4-12 and 4-13 give the initial design of sensor locations for the first two test runs. Improvements to temperature monitoring procedures were realized throughout the demonstration program. Only 13 sensor locations were monitored during testing with Cell 1. For Cell 2, 42 temperature sensors were used to obtain a better description of heat distribution within the cell. For Cells 3 and 4, pipe wall temperatures were also determined by locating several sensors adjacent to the hot air injection piping. The optimum temperature sensor distribution was developed and used with Cell 5. Figures 4-14, 4-15, and 4-16 show the sensor locations for Runs 3, 4, and 5, respectively.

4.4.4 Pre-Demonstration Sampling

Pre-demonstration sampling was conducted for the parameters listed in Tables 4-2 to 4-6 to characterize the soil, the contaminant type, and composition. To characterize the soil, four samples were analyzed for clay content, soil porosity, moisture content, and particle size distribution. Twenty soil samples were collected to determine the contaminant types and distribution within the treatment cell.

4.4.5 Technology Operation

During the demonstration, soil samples were collected and analyzed to evaluate the rate and degree to which petroleum hydrocarbons were being removed from the soil. The sampling frequency for each run is given in Tables 4-2 to 4-6. The samples were collected according to EPA protocols and sent to a contract laboratory with a 24-hour turnaround time. The availability of this data along with field thin layer chromatography (TLC) measurements allowed proper control of the process during the operation.

4.4.6 Post-Demonstration Sampling

The treatment operation was terminated when the TLC data and the contract laboratory data indicated the contaminant levels to be below regulatory standards. The criteria were 1,000 mg/kg for lubricating and heavier oil, 250 mg/kg for diesel, and 100 mg/kg for gasoline. The number of post-treatment samples that were collected for analysis are given in Tables 4-2 to 4-6. In addition, confirmation samples for each soil pile were collected by an independent contractor prior to hauling the treated soils off the test site.

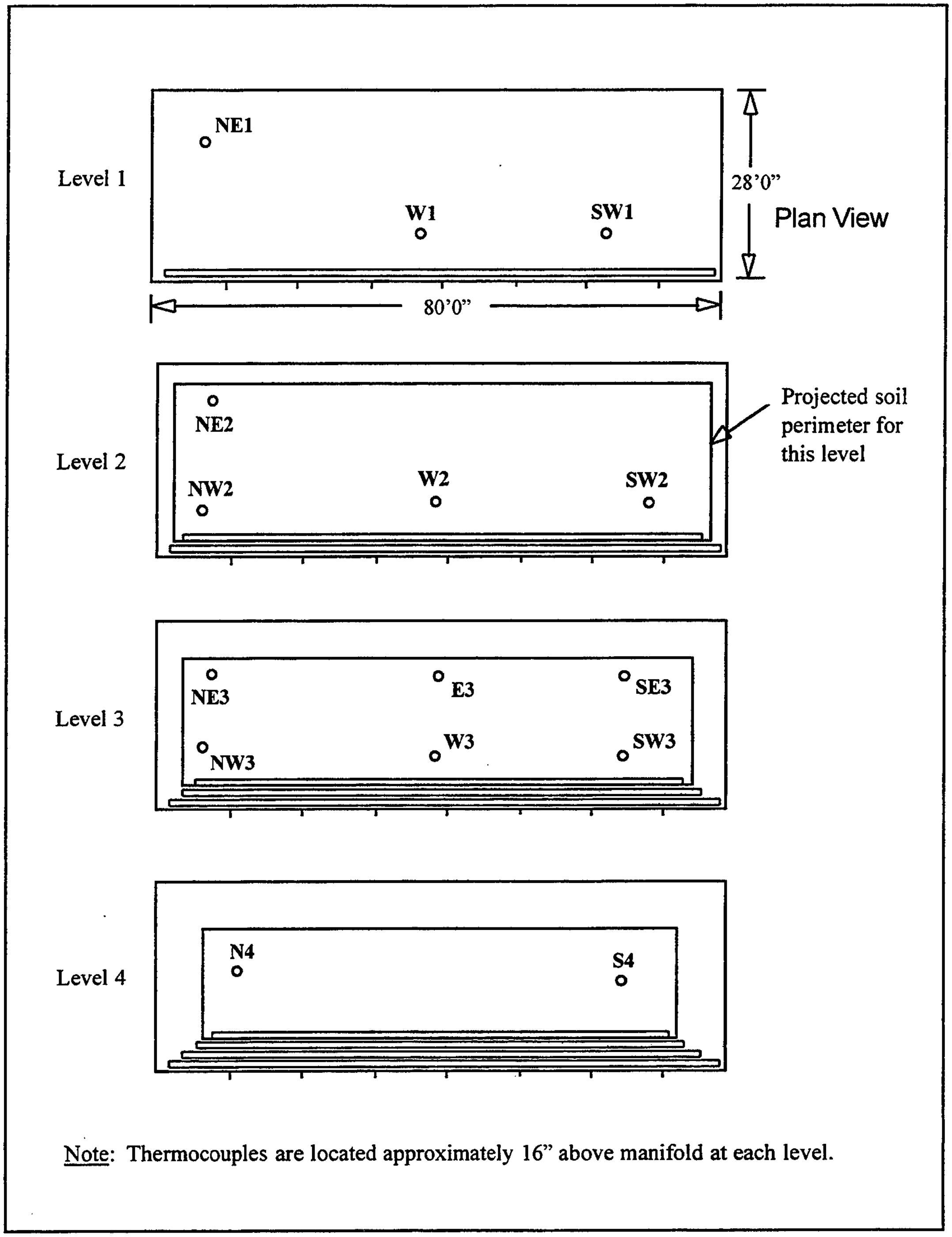
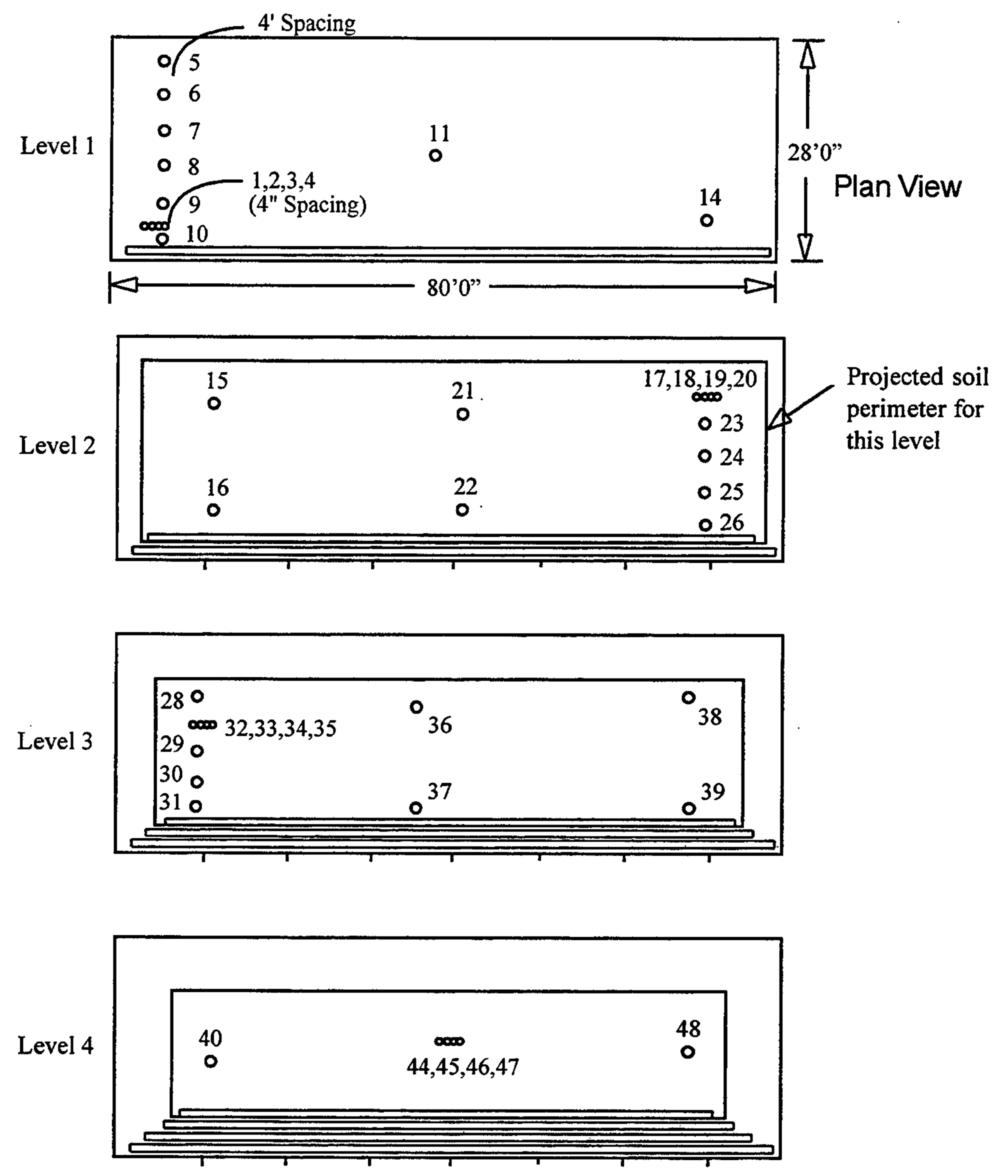


Figure 4-12. Temperature Sensor Locations for Cell No. 1



Note: Thermocouples for levels 1 through 4 are located at heights of 0'8", 3'4", 6'0", and 8'8", respectively.

Figure 4-13. Temperature Sensor Locations for Cell No. 2

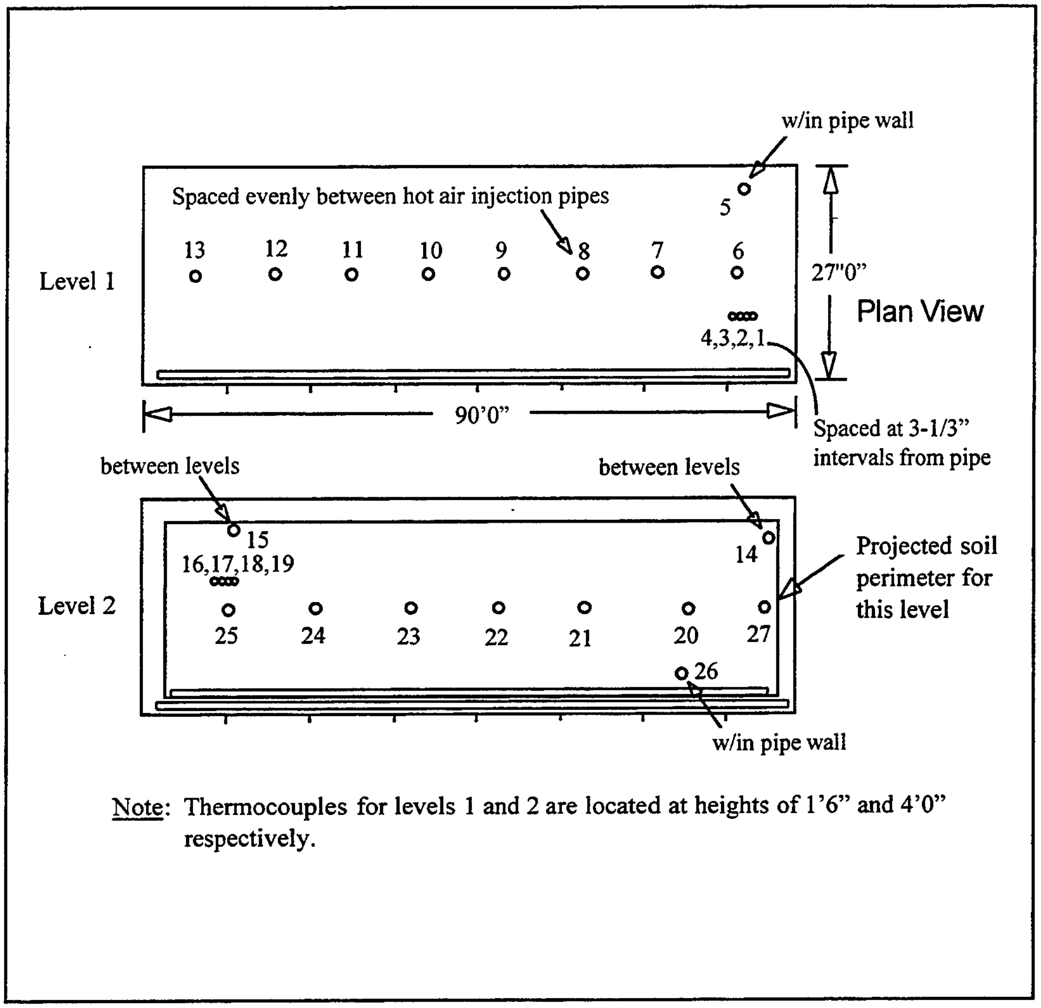


Figure 4-14. Temperature Sensor Locations for Cell No. 3

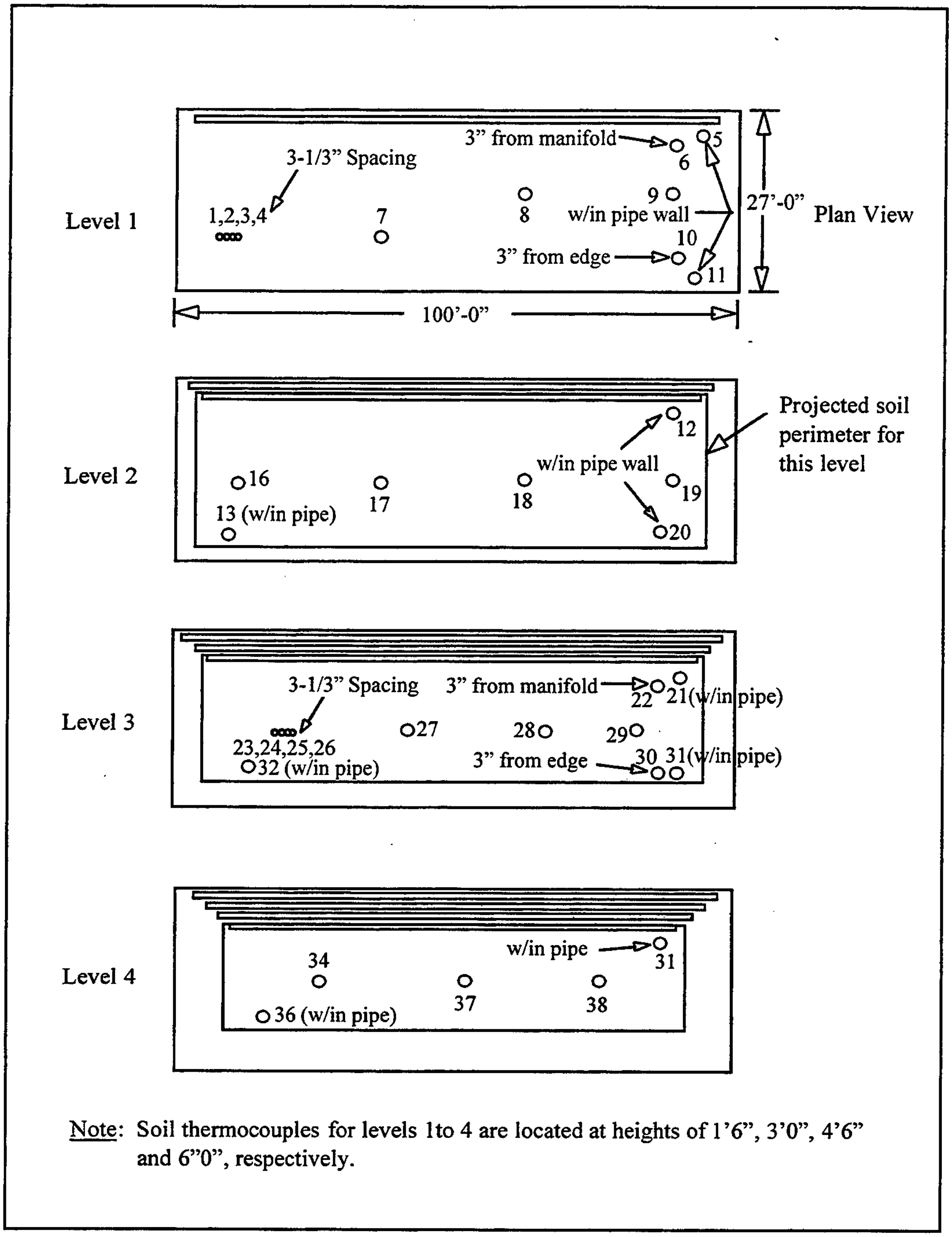
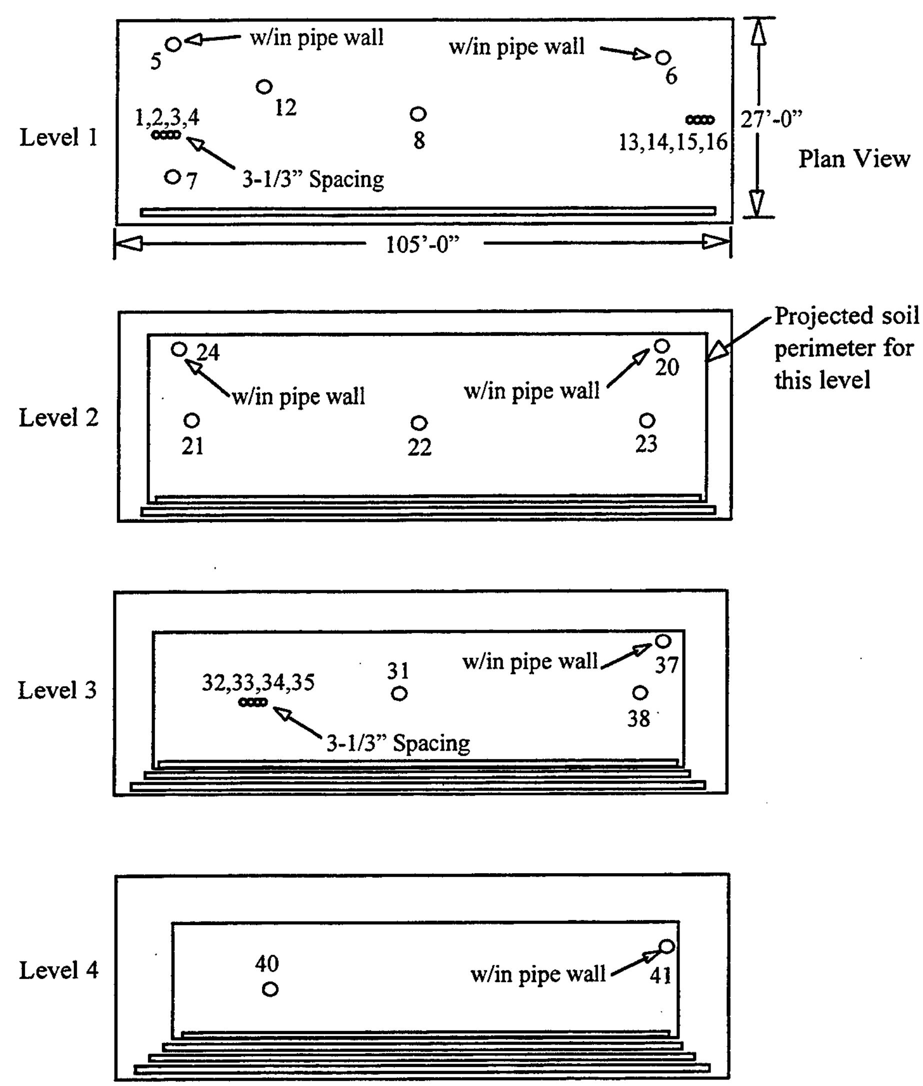


Figure 4-15. Temperature Sensor Locations for Cell No. 4



Note: Soil thermocouples for levels 1 to 4 are located at heights of 2'0", 3'6", 5'0" and 6"0", respectively.

Figure 4-16. Temperature Sensor Locations for Cell No. 5

5.0 TECHNOLOGY PERFORMANCE EVALUATION

This section summarizes the effectiveness of the HAVE technology with respect to remediation objectives and process performance. The objectives are presented in Section 2.1 and the system process is described in detail in Section 4.0.

5.1 PERFORMANCE DATA

This section presents the data generated from samples collected and parameters measured during the operation of the HAVE system. The data have been compiled for use in evaluating the system performance and remediation effectiveness. The data are presented in terms of process stream characterization in Sections 5.1.1 and 5.1.2. Mass balances were not performed since the quantity of carbon introduced from fuel combustion is much larger than that from the combustion of the hydrocarbon contaminants.

The demonstration consisted of two phases and five separate evaluation periods, referred to as Run 1 through Run 5. Each of the runs differed in terms of the mix of parameters that were varied. These parameters consisted of contaminant type, soil type, soil moisture content, and soil treatment temperature. For a given contaminated soil, the only major parameter that could be varied was the average soil temperature during treatment. The first two runs examined the performance of the HAVE system under low temperature operating conditions with gasoline and mixed fuel contaminated soils. The latter three runs tested the capability of the HAVE system to remediate soils contaminated with heavy oils, lubricating oils, and heavier fractions at higher soil temperatures. Table 5-1 shows the values of the parameters for the five runs.

During the operation of the HAVE system several process parameters were monitored by collecting soil and vapor samples, and through on-line monitoring. Soil samples were split for analysis at off-site laboratories using gas chromatography (GC), and for on-site monitoring using TLC. Soil moisture, contaminant type, and concentration data were obtained from these analyses. Soil temperature, soil vapor hydrocarbon concentrations, and air emissions were tracked through on-line monitoring. The results for the major monitoring parameters for the five runs are discussed in detail in Section 5.2.

The target remediation levels to meet the State of California standards for various petroleum hydrocarbon fractions are given in Table 5-2. The volatiles and semi-volatiles ranging from gasoline to kerosene fraction are included in C4 to C13.

The criterion for selecting the ultimate operating conditions from Table 5-1 was the reduction of contaminant concentrations below target levels in samples collected from the system throughout the treatment period. Table 5-3 displays average contaminant concentration values for each of these five runs. The soil samples were taken at the sampling points illustrated in the Figures 4-5 to 4-9 in Section 4.4. For all treatment cells except Cell 3, samples were taken from

Table 5-1. Major Variables Associated with Demonstration Runs

Run	Elapsed Time (days)	Soil Type (% Clay)	Soil Moisture (%)	Contaminant Type	Average Soil* Temperature (°F)
1	3.0	7	10.7	Gasoline	132
2	14.0	19	11.5	Diesel (57%)	150
3	6.0	15	8.0	Heavy Oil+** (81%)	212
4	14.5	19	4.4	Fuel Oil+** (67%)	410
5	11.5	3	11.5	Fuel Oil+** (73%)	310

* Indicates soil temperature at the end of treatment.

** + Indicates the percentage, includes fractions heavier than the stated petroleum fraction.

Table 5-2. Target Remediation Levels

Contaminant	Gasoline C4 to C13	Diesel and Fuel Oil C14 to C22	Heavier Fractions C23+
Target Level (ppm)	100	250	1,000

Table 5-3. Pretreatment Contaminant Concentration Distribution

Run	Gasoline C4 to C13 (ppm)	Diesel C14 to C18 (ppm)	Heavy Oil C19 to C22 (ppm)	Lube Oil C22 to C30 (ppm)	HF* C30+ (ppm)	Average TPH (ppm)
1	160	0	0	0	0	160
2	86	6,933**	-	1,527***	-	8,537
3	23	24	28	68	34	177
4	58	1,858	1,220	2,207	465	5,807
5	166	1,103	931	1,642	863	4,705

* Indicates fractions heavier than C30.

** Includes C19 to C22.

*** Includes fractions heavier than C23.

four different cell levels at a number of spatially distributed locations. Treatment Cell No. 3 had only two levels due to the smaller volume of soil treated. The TPH concentrations and standard deviations are shown in Table 5-4 for the five runs. These data indicate a substantial spatial variation in TPH concentration in the soil piles.

The post-demonstration concentrations of the various petroleum hydrocarbon fractions are shown in Table 5-5. Detailed results on daily reductions in concentration of the various contaminants for each run are given in Section 5.2. As noted previously, Run 4 was a continuation of Run 2 at a higher soil temperature. As evident from the results, low temperature operation of the HAVE system remediated gasoline contaminated soils to non-detectable levels. Diesel, heavy oil, and lubricating oils treated in Runs 3 to 5 were remediated to target levels by operating the HAVE system at higher temperatures. In addition, the duration of treatment is longer due to the lower volatility of these hydrocarbons. Table 5-6 provides data on the post-treatment TPH concentrations and the standard deviations.

5.1.1 Process Stream Characterization - Soil and Soil Vapor Samples

Soil samples were collected during HAVE system operation through prefabricated sampling ports in the membrane cover. Approximately 700 samples were collected during the demonstration. The samples collected each day were split for analysis by an off-site certified laboratory and for on-site field analysis using TLC. The data presented in Section 5.2 are from off-site contract laboratory analysis. The TLC data were available at a quick turnaround time, and were used for the purpose of monitoring treatment progress and process control.

The number of samples collected for each run, and the parameters analyzed are presented in Section 4.4. As a minimum, all samples were analyzed for TPH concentration and moisture content. TPH concentrations were measured for all soil samples using the modified EPA method 8015. The chromatograms were broken down into carbon number ranges by the analyst. For the gasoline contaminated soil in Run 1 and the mixed fuel soil in Run 2, the ranges reported were C4 to C13, C14 to C22, and fractions heavier than C23 (C23+). It was determined during Run 2 that considerable amounts of heavy oils, lubricating oils, and heavier fractions were present in the soil. For all the subsequent demonstration runs, the higher carbon ranges were broken down further to C14 to C18, C19 to C22, C22 to C30, and C30+. No separate analyses were done for volatile components using purge and trap methods.

All samples were analyzed for soil moisture content by the contract laboratory. As discussed in Section 5.2, soil moisture is a key parameter that can be related to treatment progress, and also used to adjust the distribution of hot air to different injection levels.

Passive soil vapor sampling was conducted for the gasoline contaminated soil pile using Petrex samplers. Petrex gas collection tubes contain a ferromagnetic wire coated with activated carbon adsorbent, which after exposure to soil gas, is analyzed in the Petrex laboratory using an Extranuclear Quadrupole Mass Spectrometer to provide mass spectral analysis to identify the

Table 5-4. Pretreatment TPH Concentrations

Run	Number of Samples	Average TPH (ppm)	Standard Deviation (ppm)
1	20	160*	NA
2	14	8537	2216
3	10	177	118
4	14	5807	NA
5	12	4705	1210

* Peak concentration

Table 5-5. Post-Treatment Contaminant Concentration Distribution

Run	Gasoline C4 to C13	Diesel C14 to C18	Heavy Oil C19 to C22	Lube Oil C23 to C30	HF* C30+	TPH (ppm)
1	ND	ND	ND	ND	ND	ND
2	0	5033**	-	1303***	-	6337
3	0	2	11	20	7	40
4	0	14	43	110	32	198
5	0	22	38	81	30	257

* Indicates fractions heavier than C30.
** Includes C19 to C22.
*** Includes fractions heavier than C23.

Table 5-6. Post-Treatment TPH Concentrations

Run	Number of Samples	Average TPH Concentration (ppm)	Standard Deviation (ppm)	Percent Reduction
1	20	ND	NA	100
2	14	6337	1662	26
3	10	40	58	77
4	14	198	204	97
5	12	257	249	95

organic vapors and gases present. Twenty canisters were placed inside the 2-inch diameter vapor monitoring piping and slid into position within the soil pile at three different levels. The tubes were withdrawn after 24 hours and sent to the laboratory for analysis. Petrex laboratory analysis did not provide any useful information to the project, and its use was discontinued for the subsequent demonstration runs.

5.1.2 Process Stream Characterization - Field Monitoring

Several process and emissions parameters were monitored during the study. The process parameters included soil hydrocarbon screening using TLC, soil vapor, temperatures within the soil and injection piping, and hot air injection rates. The exhaust from the HAVE system was monitored for emissions parameters as reported in Section 6.

5.1.2.1 Soil Contaminant Screening using TLC

Thin layer chromatography offers a quick and cost-effective field screening tool for identifying and quantifying soil contamination from semi- and non-volatile compounds. TLC analysis is based on the migration of a solvent through the sample. The distance the solvent migrates, and the size of the solvent spot, provides information on the type and concentration of contaminant when compared to the standards.

TLC screening was conducted on all 700 soil samples collected during the project. TLC provided results that were in qualitative agreement with the GC analysis from the contract laboratory for all runs except Run 1. In Run 1, the hydrocarbon concentrations were below the TLC detection range. Also, for Run 2, some difficulties were encountered in selecting solvent standard concentrations due to the presence of unknown constituents in the mixed fuel contaminated soil pile. For Runs 4 and 5, TLC analysis predicted that hydrocarbon concentrations were below target cleanup levels 24 hours before confirmation laboratory results were available. Therefore, TLC analysis is useful in monitoring treatment progress and in project planning to initiate shutdown of operations. However, TLC does not provide quantitative information, and is not a substitute for GC analysis of soil samples. TLC analyses are, therefore, not included in this report.

5.1.2.2 Soil Vapor Monitoring

Soil vapor was monitored at locations noted in Section 4.4 for Runs 1 to 4. The data obtained were inconsistent, and did not correlate with the contract laboratory data. These data provided no useful information and are not reported here.

5.1.2.3 Temperature and Air Flow Measurements

Temperature is one of the key parameters that needs to be properly controlled and adjusted to provide effective remediation. Temperatures were extensively monitored and recorded for all demonstrations, and are reported in Section 5.2.

Air flow rates through each of the injection manifolds were monitored by pre-ignition calibration of damper positions with flow rate. Representative data are provided for Run 3 in Section 5.2. Table 5-7 provides the average temperatures and air flow rates used during the tests.

Table 5-7. Average Temperatures and Air Flow Rates

Run	Hours of Treatment	Average Air Temperature (°F)	Average Soil Temperature* (°F)	Average Air Flow (ACFM)
1	72	720	132	5,500**
2	335	730	150	5,200
3	143	710	212	4,700
4	350	725	410	4,200
5	278	650	310	4,100

* Soil temperature at the end of treatment.

** Peak flow rate.

5.2 DEMONSTRATION RESULTS

The operation of the HAVE system in Phase 1 tests using the original design at low soil temperatures, and operation in Phase 2 with the modified HAVE system design at higher soil temperatures, are described in the following sections. The original and modified HAVE system configurations are shown in Figures 4-2 and 4-3, respectively. Typical cell dimensions for a modified HAVE system configuration are shown in the Appendix.

5.2.1 Phase 1 Tests Using Original HAVE System Design

Phase 1 tests were conducted to determine the efficacy of the original HAVE system design in remediating soils contaminated with gasoline and diesel range hydrocarbons. In this design, the 4-inch vapor injection ducts were covered with 2 feet of soil at the far end as shown in Figure 4-2. The following sections provide the test results and analysis for Runs 1 and 2.

5.2.1.1 Run 1 - Remediation of Gasoline Contaminated Soil Pile

The main objective of the demonstration was to determine the capability of the HAVE system to decontaminate soils containing petroleum hydrocarbons in the diesel range. As such, the first test run with gasoline contaminated soils was designed to provide baseline information on the operating characteristics of the system. Soil temperature, moisture, and TPH data along with soil vapor hydrocarbon data would be used in designing an effective monitoring plan for the subsequent demonstration runs.

Low temperature operation would take advantage of the volatility of the contaminants to effectively strip them from the soil with low energy input into the system. Results from operation of Run 1 indicate that cleanup of gasoline contaminated soils to non-detectable hydrocarbon concentration levels can be achieved at an average soil temperature of 132°F. The initial moisture content of the soil was 10.7 percent, and after 72 hours of treatment the moisture content was reduced to 10.2 percent. Thus, gasoline contaminants were removed without substantial energy input to remove moisture from the soil.

Soil Temperature

The effective distribution of the injected hot air to uniformly and rapidly heat the soils is important in efficient soil remediation using the HAVE system. Soil temperature distribution is a good measure of the effectiveness of heat transfer from the injected air to the soil. Figures 5-1 through 5-4 show the temperature progression during treatment at the monitoring locations as indicated in Section 4. The temperature distribution is fairly uniform within the first three levels, indicating an even distribution of injected air through the main ducts to the three levels. However, within each level there is a drop of about 50°F from locations close to the main injection manifold to locations farthest away. Moreover, the return air temperature shown in Figure 5-4 is much higher than the soil temperatures. This indicated substantial channeling of the injected air into the balloon surrounding the soil.

Process and Monitoring Improvements

The evaluation of gasoline soil pile data led to further refinements in the design of the monitoring plan for subsequent demonstration runs. These included the following:

- The total number of temperature sensors were increased to 41 for Cell No. 2.

- A thermocouple array was prefabricated to monitor propagation of the thermal front. The array was positioned between two sets of 4-inch injection ducts, and each thermocouple was located adjacent to the other with 4-inch spacing.

- The frequency of monitoring for cell temperatures was increased to four per day.

- Soil vapor monitoring ports were installed in each of the HAVE system's five vapor distribution ducts.

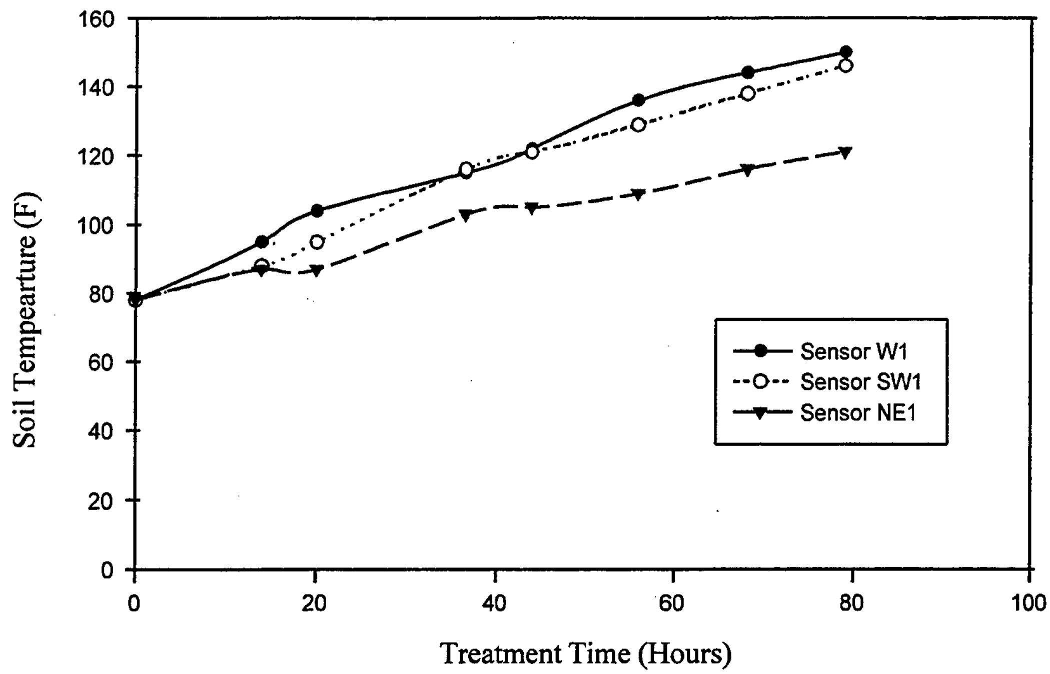


Figure 5-1. Level 1 Soil Temperatures for Gasoline Soil Pile, Cell No.1

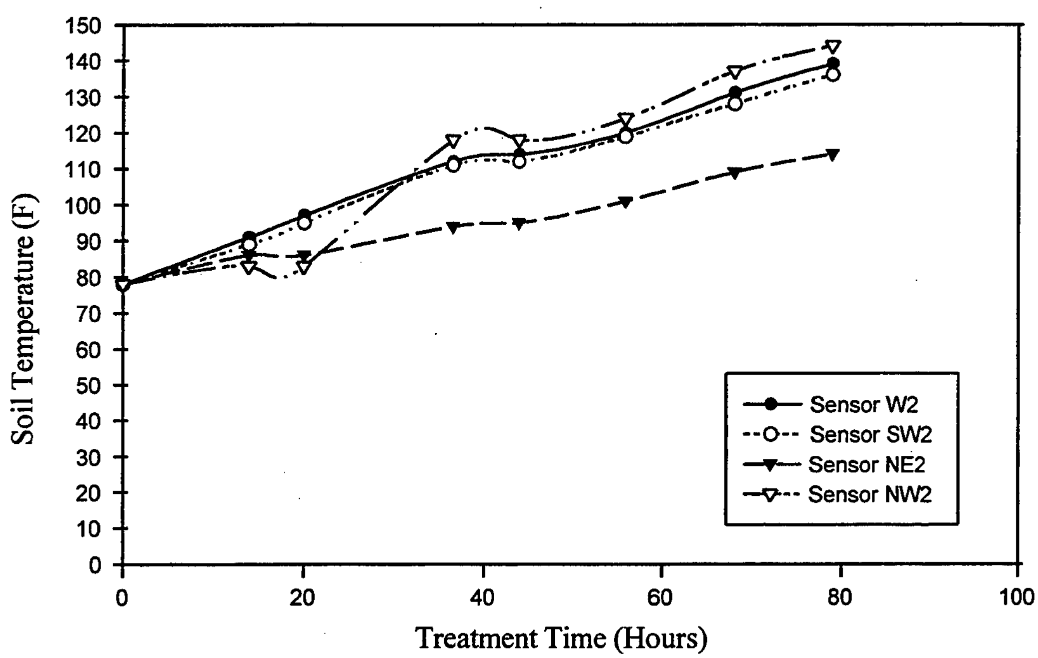


Figure 5-2. Level 2 Soil Temperatures for Gasoline Soil Pile, Cell No.1

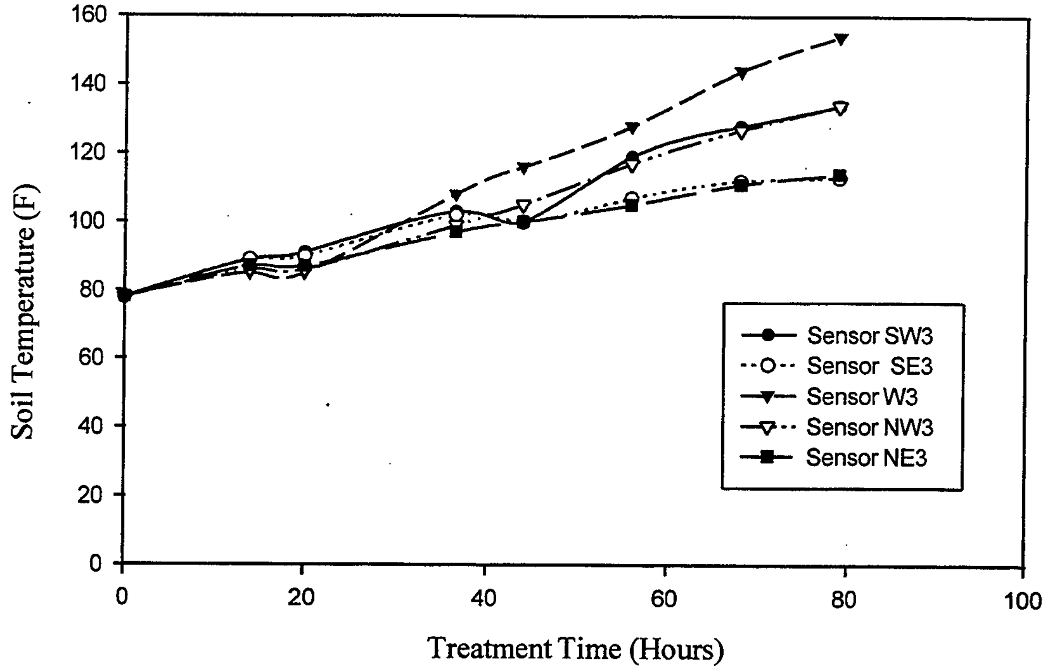


Figure 5-3. Level 3 Soil Temperatures for Gasoline Soil Pile, Cell No.1

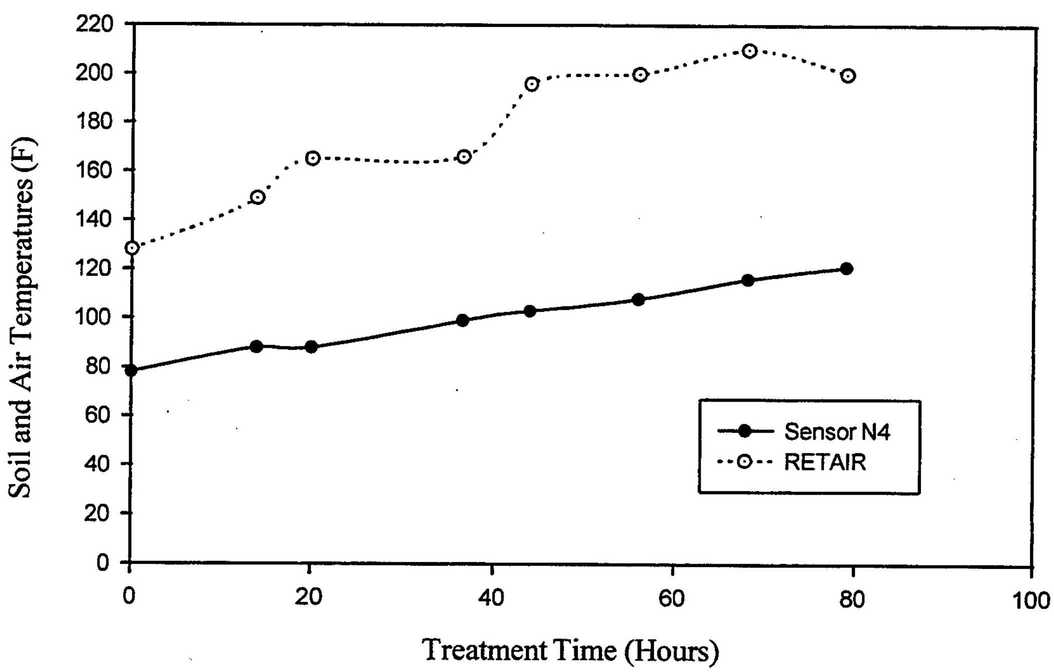


Figure 5-4. Level 4 and Return Air Temperatures for Cell No.1

- Startup procedures were modified to include pre-ignition calibration of each hot air injection duct at varying flow rates.

- Combustion furnace operating parameters were optimized to provide maximum air flows through the soil pile.

5.2.1.2 Run 2 - Remediation of Mixed Fuel Contaminated Soil Pile

The mixed fuel soil pile was treated in the original cell configuration with the test plan modifications noted under Section 5.2.1. The treatment period over a period of 14 days resulted in the removal of about 4,000 pounds of hydrocarbons. However, the soil was not remediated to the regulatory standards due to the relatively low volatility of the contaminants, the low soil temperature achieved, and the high clay and moisture contents of the soil.

The soil remediated in Cell No. 2 contained about 32 percent hydrocarbons in the diesel fraction, and 67 percent in heavier fractions as indicated in Table 5-1. The higher hydrocarbons have boiling ranges from 600°F to 1,000°F. Moreover, the clay content of the soil was 19 percent, and the initial moisture content was 11.5 percent. A combination of this matrix of parameters inhibited technology performance to meet target remediation levels. However, as discussed below, based on an evaluation of this demonstration run data, the HAVE system was modified to treat similar types of soils effectively in the subsequent runs.

<u>TPH and Soil Moisture</u>

The change in contaminant concentration distribution and the change in TPH concentration during treatment are shown in Figures 5-5 and 5-6. There is some removal of diesel and fuel oil fractions (C13 to C23) over the 14 days of operation, but there is very little removal of the C23+ fractions in the soil. Each point represents an average value from samples collected from locations within the four levels of the cell. As such, the variations in moisture levels, temperature, and clay content at various locations are manifested in fluctuations in hydrocarbon contaminant concentrations during treatment.

The average soil moisture content during treatment, and its relationship to TPH concentrations are shown in Figures 5-7 and 5-8. The soil moisture content was relatively unchanged during the first 225 hours of operation, and thereafter decreased rapidly to about 5 percent. Figure 5-4 indicates that TPH concentration is linearly related, albeit with a small slope, to the soil moisture content. Removal of low boiling fractions will occur over a period of time at the high moisture levels in the soil. However, there is very little removal of the higher boiling fractions, and in effect to remove diesel and heavier fractions, the moisture levels must be reduced to much less than the values achieved in this test. The high soil moisture levels, the high TPH concentrations, and fluctuations in these values can be explained by examining the soil temperatures achieved during operation in various levels of the cell.

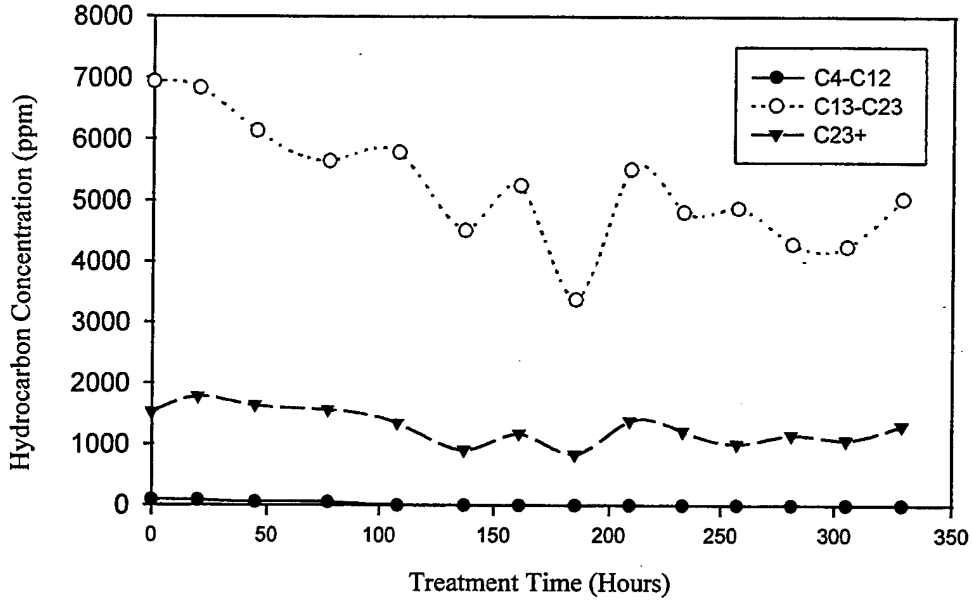


Figure 5-5. Contaminant Distribution for Mixed Fuel Soil Pile, Cell No. 2

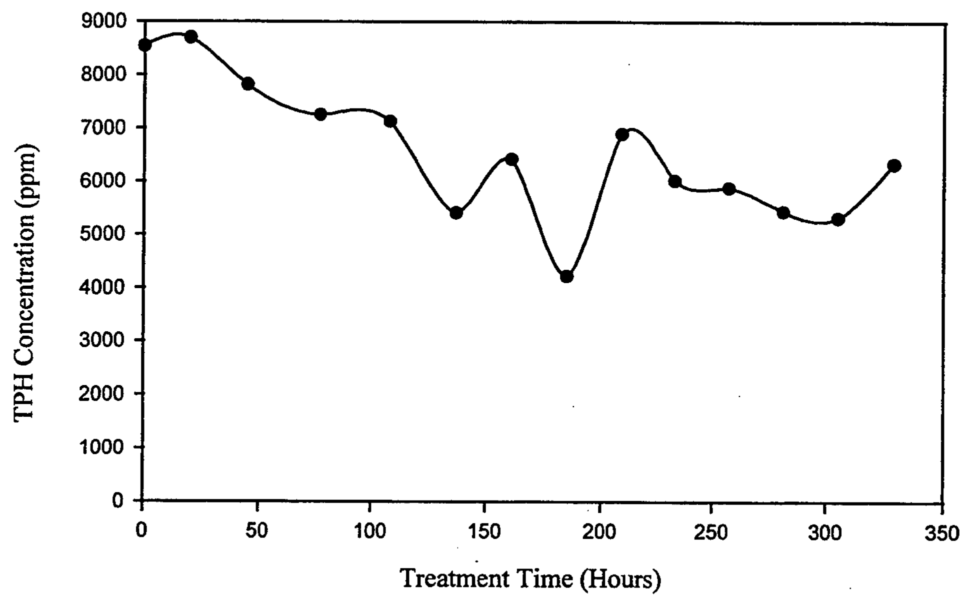


Figure 5-6. Treatment Progress for Mixed Fuel Soil Pile, Cell No. 2

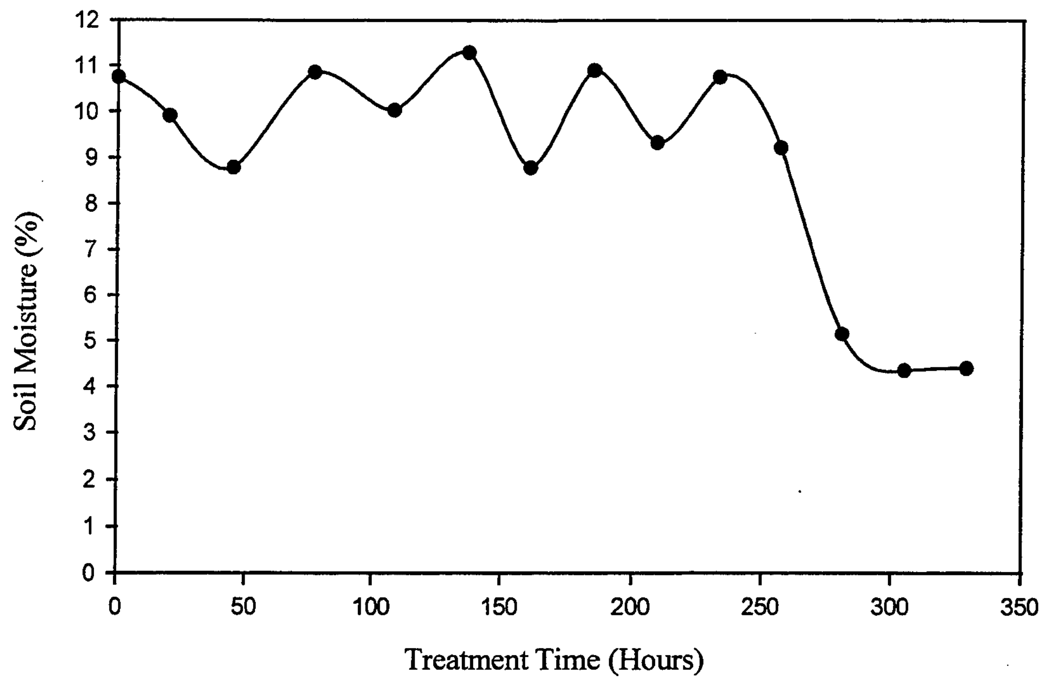


Figure 5-7. Soil Moisture Content for Cell No. 2

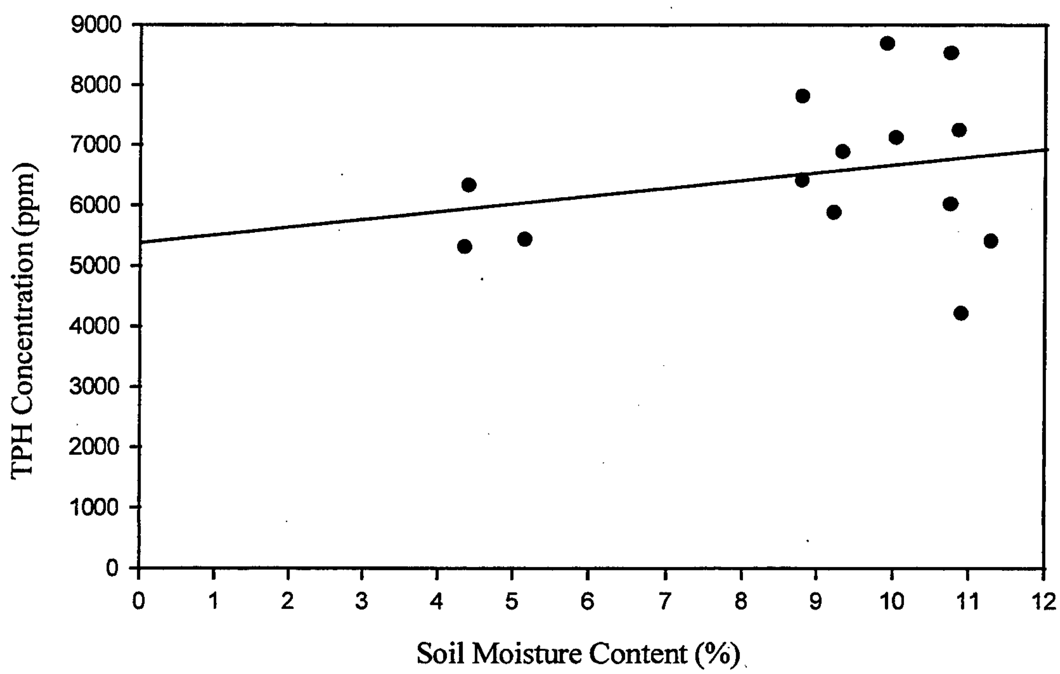


Figure 5-8. Soil Moisture Content and TPH Relationship for Cell No. 2

Soil Temperature

Soil temperatures within the pile were quite extensively monitored with 41 sensors for the mixed fuel soil pile during Run No. 2. The average injection air temperature was 730°F, and the average soil temperature attained over the whole cell was 150°F. Figure 5-9 shows the soil temperatures within the first level, right adjacent to the first level injection manifold (sensor T10), and at 4 foot intervals from the manifold. The farthest sensor (T5) is located 20 feet from the injection manifold. Soil heating was slow, reaching a temperature of 200°F close to the manifold after about 3 days. Farther away from the manifold, soil temperatures ranged from 160°F to 120°F. The temperature close to the manifold increased to 400°F after 8 days, and after a brief excursion to 600°F gradually returned to 480°F at the end of 14 days. The soil temperature away from the manifold reached 200°F at a distance 4 feet from the manifold and 150°F at a distance of 20 feet at the end of 14 days. Soils in levels 2, 3, and 4 reached a maximum temperature of 160°F, as shown in Figures 5-10 to 5-12.

The soil moisture profile (Figure 5-7) is consistent with the data from the temperature profiles. During the first 250 hours of operation, the mean temperature was much less than 200°F throughout the cell, and hence there was very little change in moisture content. Moreover, wide variations occurred in the TPH and moisture values throughout the cell due to the spatial temperature variations. After about 250 hours of operation, there was a decrease in moisture levels due to an increase in temperatures to above 200°F at locations close to the injection manifolds.

Temperature has been shown to be one of the most important parameters for effective thermal desorption of contaminants from soil (Lighty, et al., 1989; Szabo, et al., 1989). The soil temperature must be increased sufficiently to substantially increase the vapor pressure of the contaminants. Under such conditions, the HAVE system can be effective in convective transport of the contaminants from the soil pores.

Process Improvements

Computer modeling studies indicated that the treatment cells as configured for Runs 1 and 2, and the operation of the HAVE system resulted in little convective heat and mass transfer from the soil. Conductive heat transfer from the interstitial air in the balloon area was found to be a significant contributor to the overall remediation efficiency of the system. Attempts to increase the soil temperature by further increasing the balloon temperature above 200°F resulted in melting of the Canvex fabric.

The need to maintain higher and uniform soil temperatures for effective remediation of soils contaminated with high boiling petroleum fractions was recognized from the evaluation and analysis of the demonstration data from Run 2. To maintain a higher temperatures, a membrane fabric that can withstand the temperature and wind load was required.

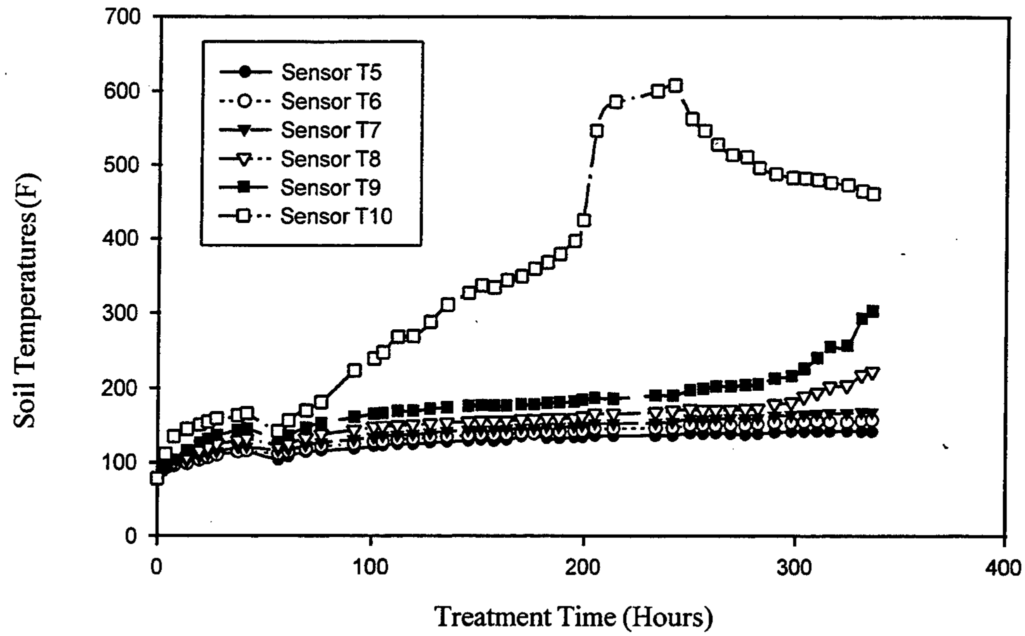


Figure 5-9. Level 1 Soil Temperatures for Mixed Fuel Soil Pile, Cell No.2

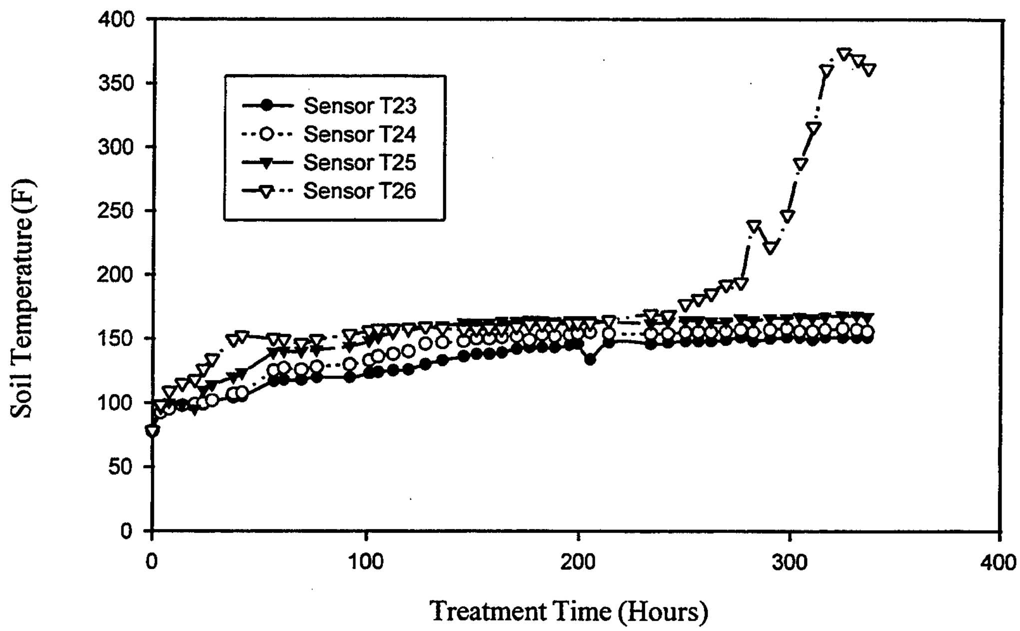


Figure 5-10. Level 2 Soil Temperatures for Mixed Fuel Soil Pile, Cell No. 2

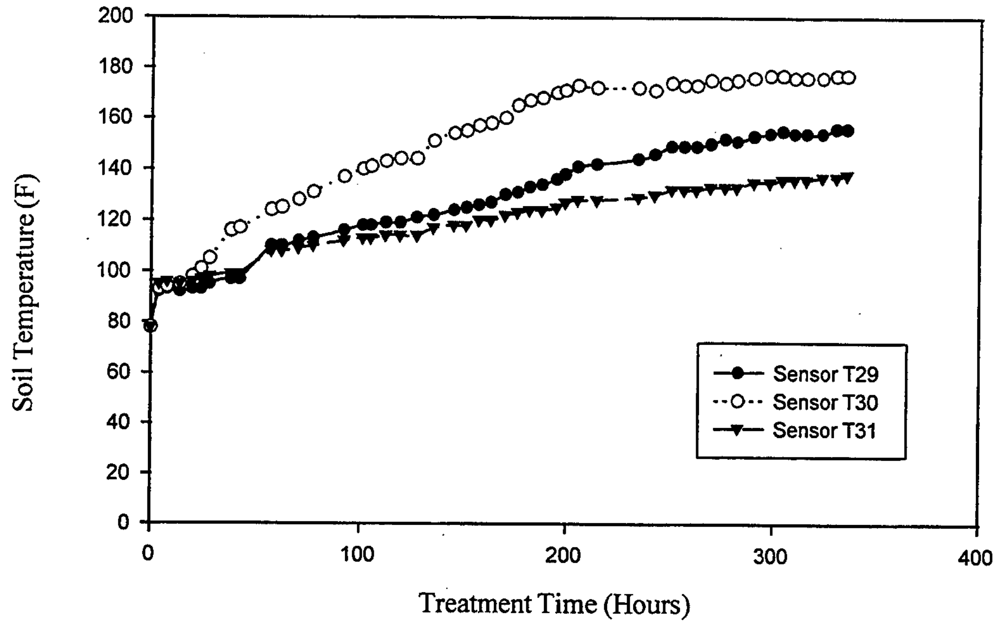


Figure 5-11. Level 3 Soil Temperatures for Mixed Fuel Soil Pile, Cell No.2

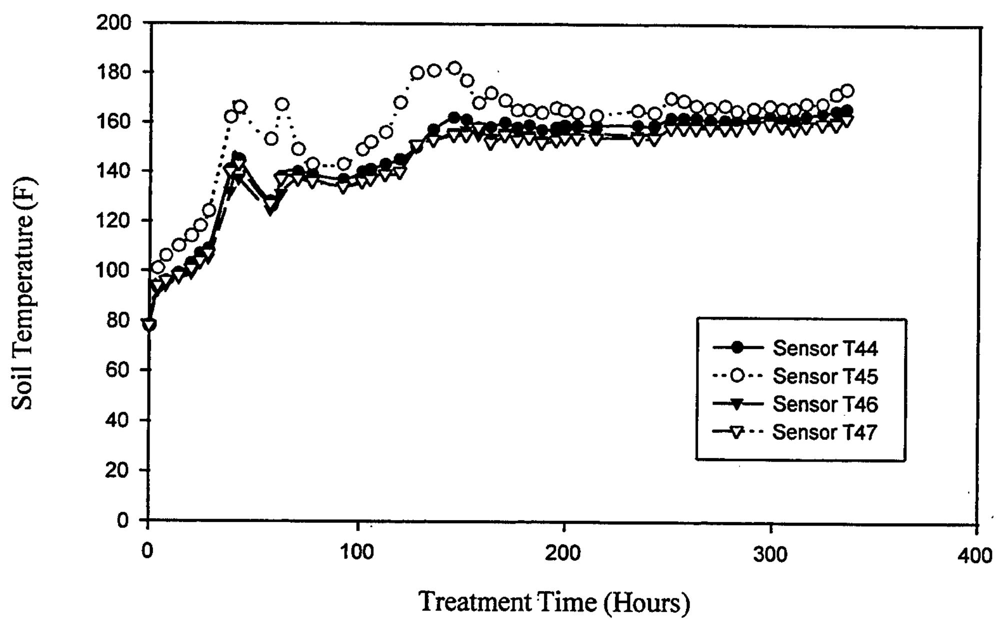


Figure 5-12. Level 4 Soil Temperatures for Mixed Fuel Soil Pile, Cell No.2

The following modifications were made for the construction and operation of Cell No. 3:

- The HAVE system design was modified as shown in Figure 4-3 to reduce the temperature gradient from the injection manifold to the extremities of the 4-inch vapor distribution ducts.

- The spacing between the bottom of the pile to the first injection duct was changed to 18 inches, and the space from the first to the second level duct was changed to 30 inches.

- Temperature sensors were installed at 20-foot intervals at each level, at 4-inch distances from the injection pipe, and at the perimeters of the treatment cell.

- Temperature sensors were installed in the hot air injection pipes.

- Aluminized fiberglass was used for covering the cell.

5.2.2 Phase 2 Tests Using Modified HAVE System Design

Three demonstrations were conducted, namely, Runs 3, 4, and 5 to determine the efficacy of the HAVE system to remediate soils containing heavy oils and mixed fuels. As shown in Figure 4-3, the 4-inch hot air distribution pipes extended to the soil perimeter and were exposed at the end to allow more air flow to the section of the pile farthest from the main injection ducts. The cells were also constructed somewhat shallower than before. The three cases had different contaminant compositions, soil moisture content, and clay content. In all cases, the modifications made to HAVE system design and operation were found to be sufficient to remediate the contaminated soils to target levels. The following sections provide the data and analyses of demonstration Runs 3, 4, and 5.

5.2.2.1 Run 3 - Remediation of Heavy Oil Contaminated Soil Pile

The heavy oil contaminated soil pile volume was 350 cu. yds., and a cell with two hot air injection layers was constructed to treat this pile. The contaminants in this pile included significant amounts of lubricating oil and heavier fractions (see Table 5-2). The boiling point range for these contaminants is about 600°F to 1,000°F, and hence the temperature of the soil must be sufficiently high to increase the vapor pressures of these contaminants. The clay and soil moisture contents of the soil were sufficiently high at 15 percent and 8 percent, respectively, to potentially inhibit process performance. However, due to the increased conductive heating and convective heat and mass transfer, the new HAVE system design remediated the soil to below target levels.

TPH and Soil Moisture

The contaminant distribution and the TPH concentration history during the 6 days of operation for Run No. 3 are shown in Figures 5-13 and 5-14. The gasoline fraction was effectively removed within 20 hours of operation. The percent removal of the other contaminants during the first 20 hours decreased with decreasing relative volatility. The contaminant concentrations were relatively constant thereafter, until about 90 hours of operation. During this latter period, there was a rapid decrease in contaminant concentration.

The data for treatment progress is consistent with the soil moisture profile shown in Figure 5-15. During the first 30 hours of operation, the soil moisture content decreases from 8 percent to about 4 percent, and some of the low boiling hydrocarbons are distilled off with the moisture. Thereafter, the soil moisture is constant, and does not decrease until about 90 hours of operation. Results from Runs 2 and 3 clearly indicate that for soils having a high clay content, the soil moisture bound to the clay matrix may be harder to remove without increasing the soil temperature substantially. Further, as shown in Figure 5-16, the TPH concentration is directly related to the soil moisture content. This indicates that while the HAVE system is capable of remediating soils contaminated with heavy oil and higher petroleum fractions, it is important to tailor the system design and operation to each specific case, taking into account the soil matrix and contaminant matrix at the site.

Soil Temperature

The temperature history was carefully monitored within the soil pile at several locations, at both ends in the 4-inch injection pipe, and in the balloon. A total of 24 sensors was used, and readings were taken every 6 hours. Figure 5-17 shows the temperature profiles in Level 1 at mid-pile at 10-foot intervals along length of the pile. Soil heating was more rapid and uniform with the new HAVE system design, increasing to 140°F to 160°F after 32 hours of operation. All the sensors except T10 located at the center of the pile were within 10°F of each other, indicating uniform air distribution within the cell. The temperatures ranged from 160°F to 180°F after 96 hours of operation, and at the end of the treatment period the temperatures ranged from 170°F to 190°F. The soil temperatures followed almost a similar pattern in Level 2, except that the temperatures at all locations were within about 10°F of each other (see Figure 5-18). Also, the temperatures were somewhat higher, reaching between 180°F and 203°F after 100 hours of operation, and 184°F to 271°F at the end of operation. The TPH and moisture removal data are consistent with the temperature histories in the two levels.

The temperature histories close to the 4-inch vapor injection pipes were monitored using a cluster of thermocouples located 4 inches apart sequentially from the injection pipe. This was done to assure consistency of measured data, and to determine the soil temperature gradients in the pile. Figure 5-19 shows the temperature adjacent to the 4-inch pipe (sensor T1) increases rapidly to 300°F at 32 hours, decreases and remains at 270°F from 56 to 79 hours, and thereafter

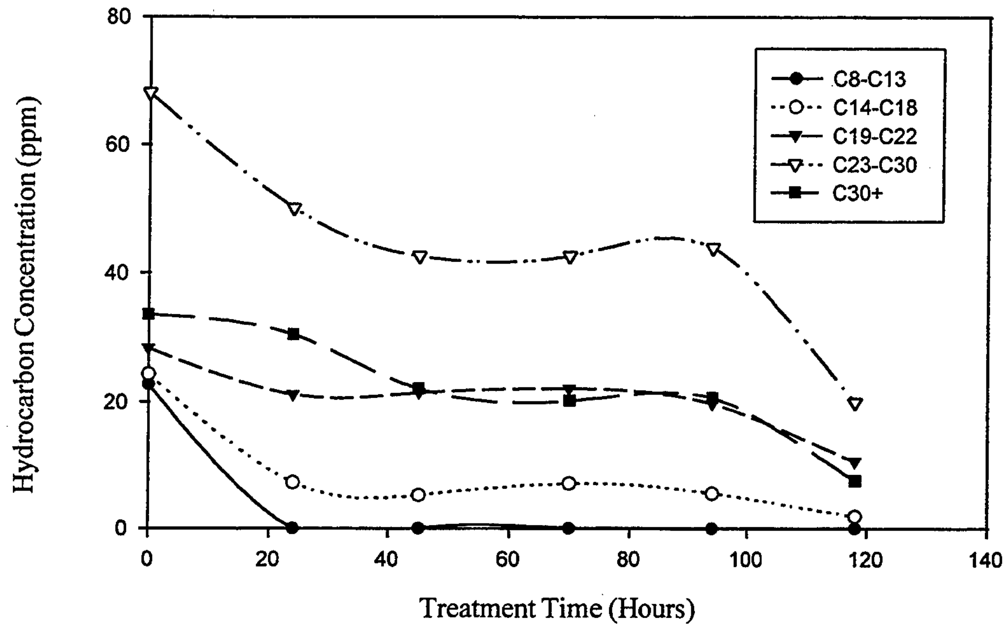


Figure 5-13. Contaminant Distribution for Heavy Oil Soil Pile, Cell No. 3

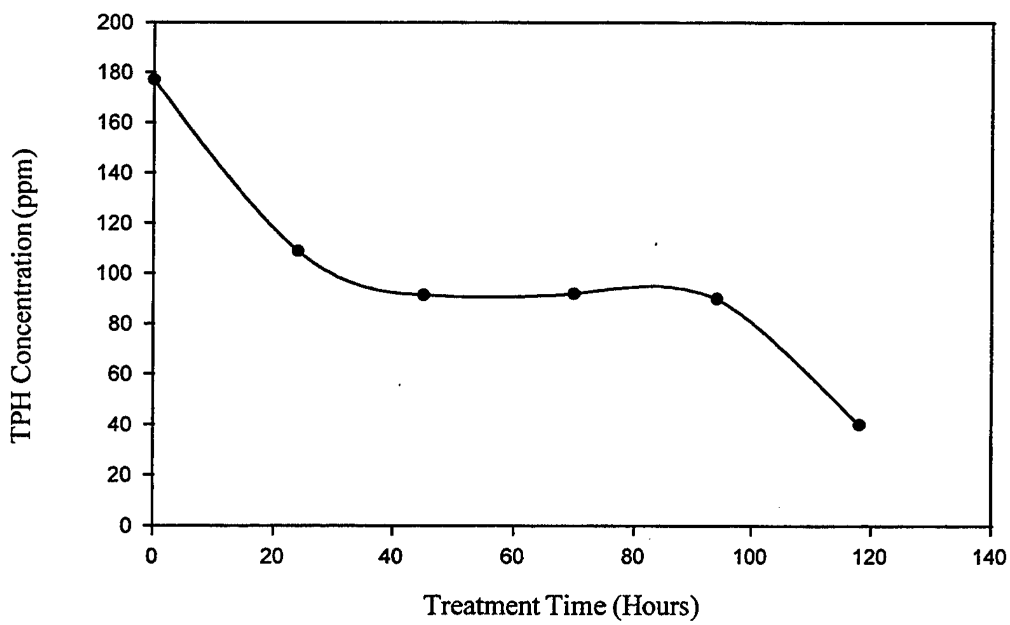


Figure 5-14. Treatment Progress for Heavy Oil Soil Pile, Cell No. 3

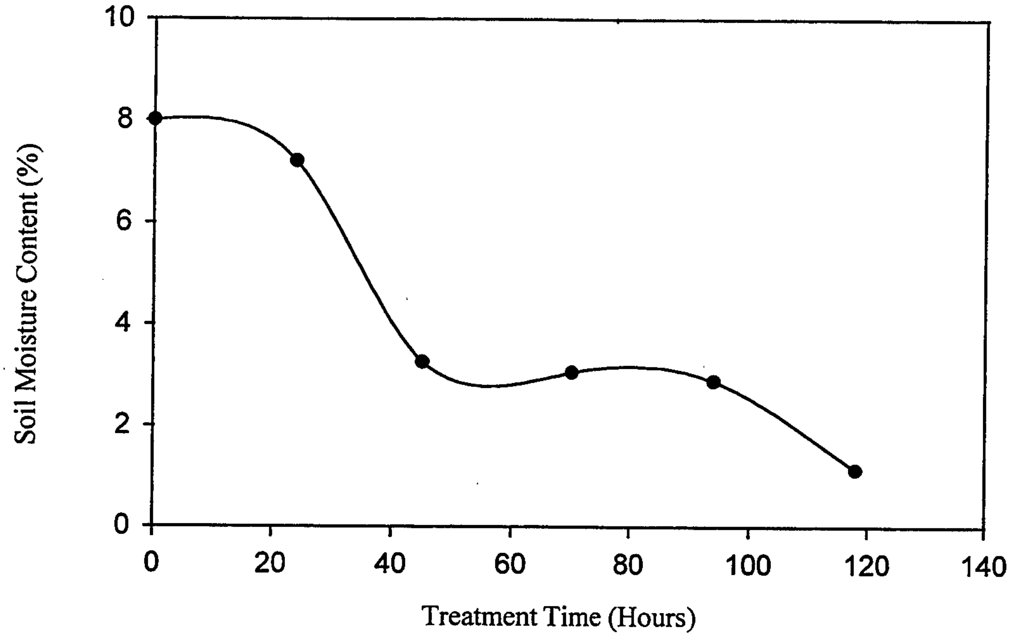


Figure 5-15. Soil Moisture Content for Cell No. 3

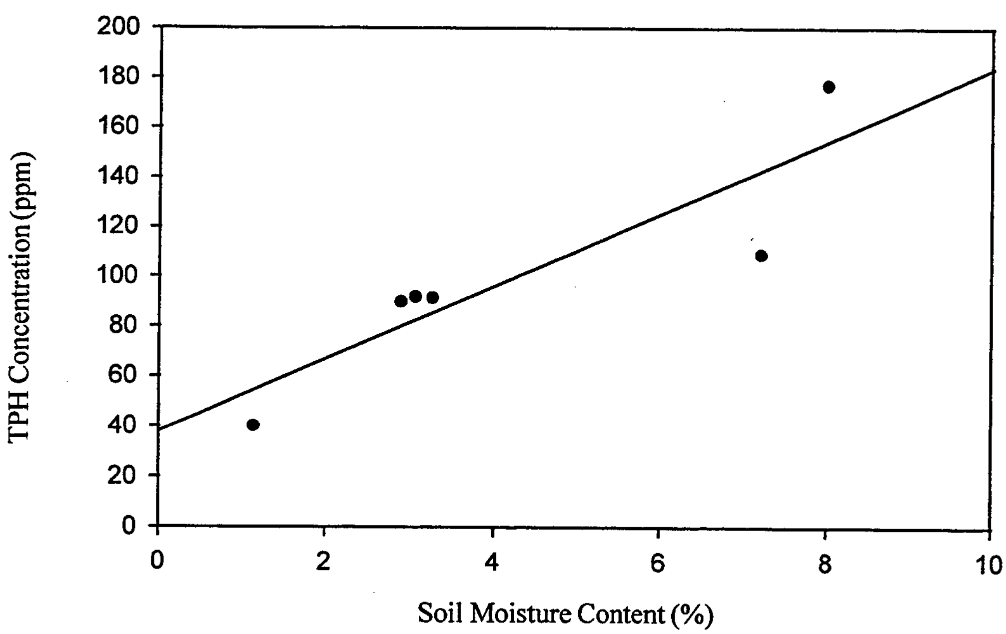


Figure 5-16. Soil Moisture and TPH Relationship for Cell No. 3

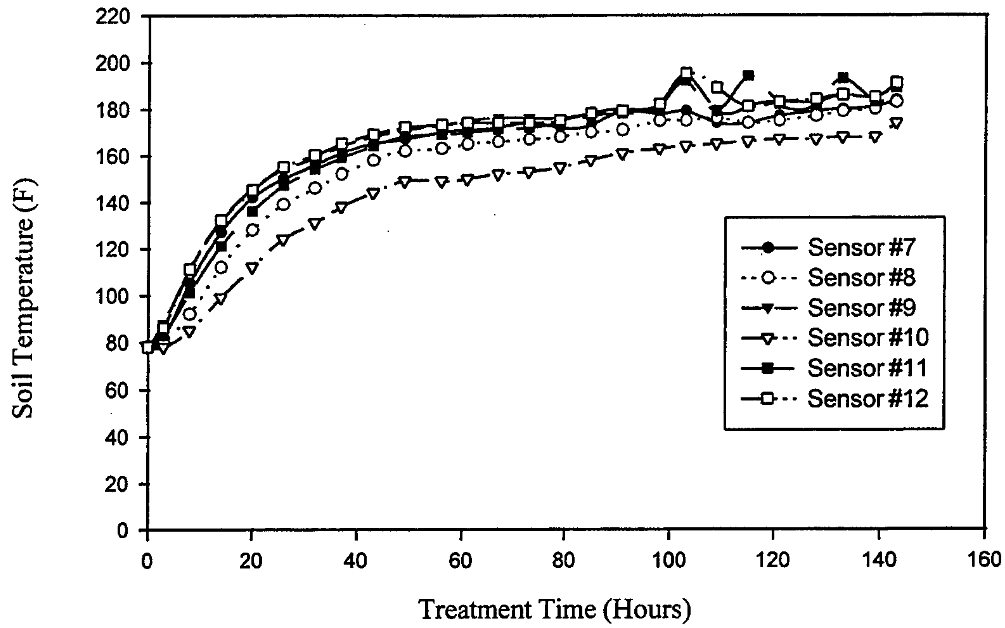


Figure 5-17. Level 1 Soil Temperatures for Heavy Oil Soil Pile, Cell No. 3

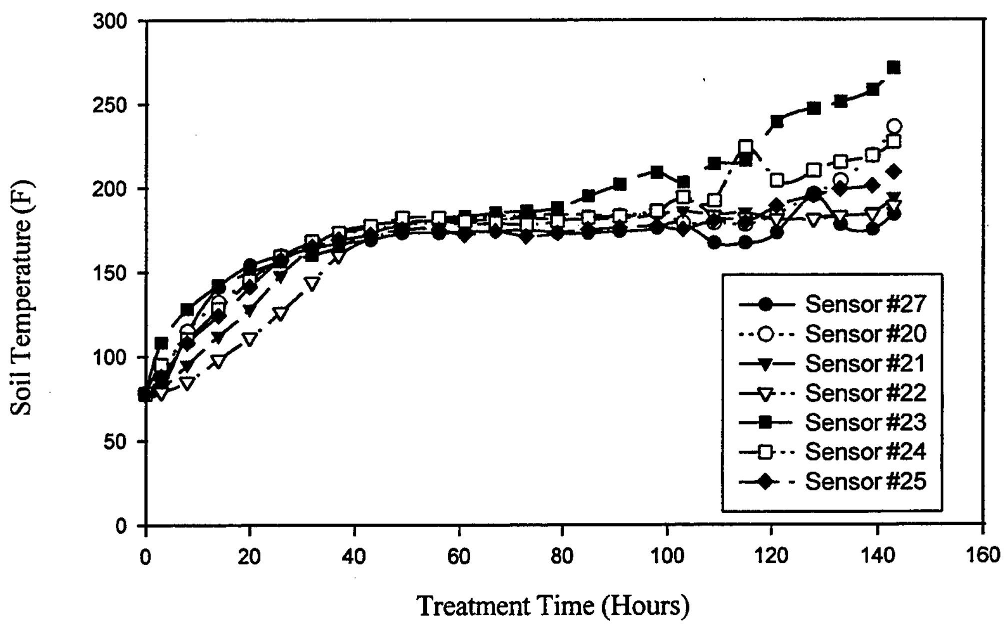


Figure 5-18. Level 2 Soil Temperatures for Heavy Oil Soil Pile, Cell No. 3

steadily increases to 350°F. The sensors T2 to T4 show a steady increase in temperature with little fluctuations. The temperatures are uniform and within 15°F of each other indicating a uniform hot air distribution into the soil pile. Moreover, due to the large heat capacity of the soil, a drop in the injection temperature during the 56- to 79-hour time duration showed very little effect on the soil temperatures.

Figure 5-20 displays the soil temperatures at 4-inch intervals from the 4-inch injection pipe. In Level 2, the data for sensor T16 adjacent to the pipe is not displayed due to malfunction during the first 3 days of operation. During the latter period of the study, the temperature ranged from 487°F to 505°F. The sensor closest to the pipe (T17) shows some fluctuations in temperature similar to that for T1. However, as can be seen from sensor data from T18 and T19, fluctuations are marginal at 8 inches from the injection pipe.

The air temperatures in the 4-inch pipe close to the manifold in the second level (sensor T26), and the temperatures at the end of the 4-inch pipe in the first level, are shown in Figure 5-21. The air and soil temperatures in Level 1 are somewhat lower than in Level 2 due to the smaller volume of air injected per unit volume of soil. The air temperatures in the interstitial space between the soil pile and the membrane are also shown in Figure 5-21. The balloon air temperature is consistently higher than the surrounding soil temperature indicating that some of the injected air is bypassing the soil and reaching the vapor extraction pipes.

Hot Air Injection Rates

The air and soil temperature in each level can be controlled by adjusting the dampers controlling the air flows to the manifolds serving each level. The soil temperatures and their fluctuations adjacent to the pipes are closely related to the air flow rates. Figures 5-22 and 5-23 display the air flow rates to Level 1 via Manifold 1A and Manifold 1B, and to Level 2 via Manifold 2. This is evident upon comparison of the air flow rate data and the soil and air temperature data for Levels 1 and 2. The soil temperatures in Level 2 are somewhat higher due to the larger volume of air injected per unit volume of soil treated in Level 2.

The monitoring of air flow rates, temperatures, and treatment progress in the field using TLC is useful in optimizing the operation of the HAVE system to provide effective treatment at the lowest cost. Air flow rates can be monitored and adjusted easily to provide increased flows to levels that have higher TPH concentrations.

Process Improvements

The aluminized fiberglass delaminated when unusually high winds coincided with high system temperatures. Five types of fabric, namely, (1) Teflon coated fiberglass, (2) lightweight aluminum coated fiberglass, (3) heavy weight aluminized fiberglass, (4) acrylic coated fiberglass, and (5) acrylic impregnated fiberglass, were tested using a constructed test panel at the site. The heavy weight acrylic impregnated fiberglass was chosen for use in further demonstration studies

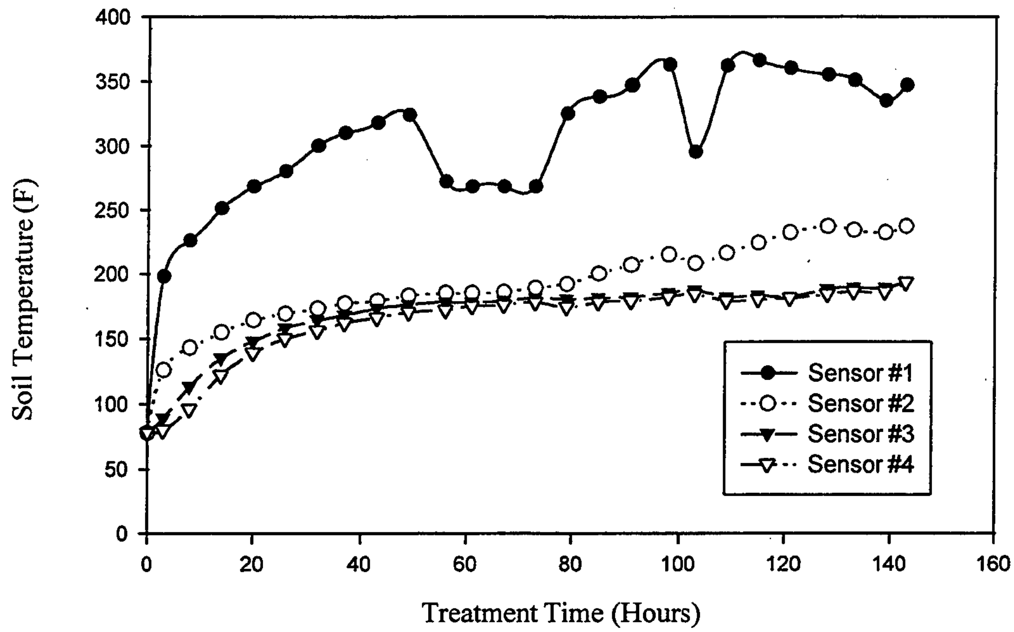


Figure 5-19. Level 1 Soil Temperatures at 4-inch Intervals from Injection Pipe, Cell No. 3

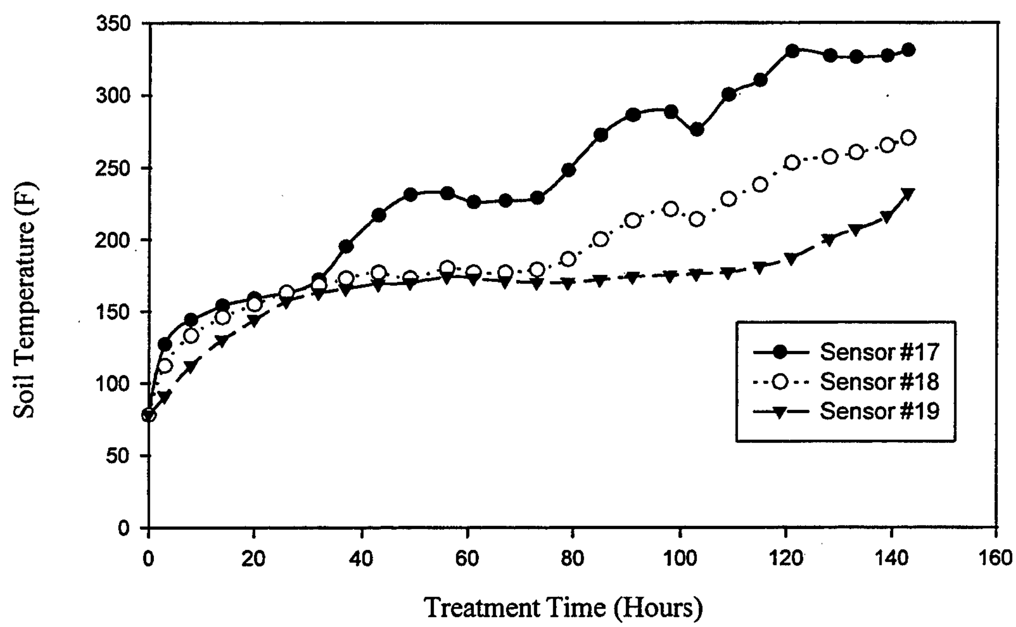


Figure 5-20. Level 2 Soil Temperatures at 4-inch Intervals from Injection Pipe, Cell No. 3

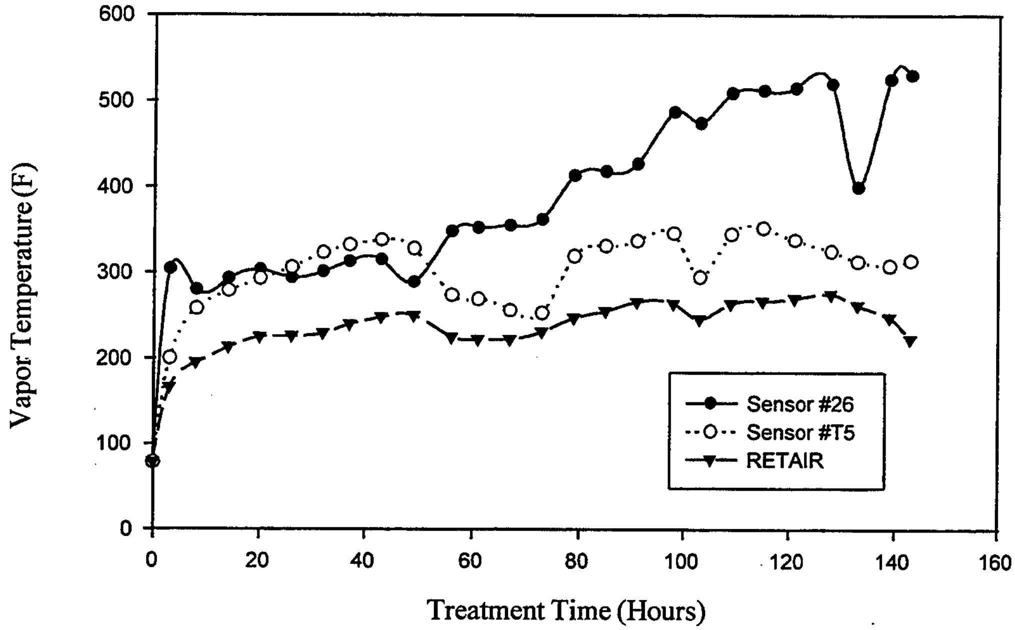


Figure 5-21. Vapor Injection, Balloon and Return Air Temperatures

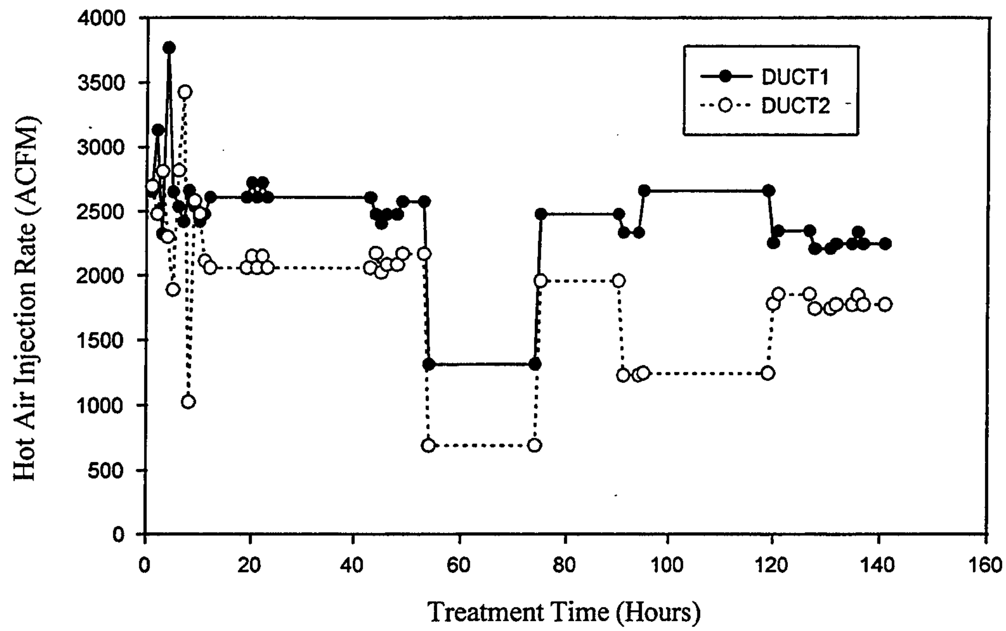


Figure 5-22. Hot Air Injection Rates for Heavy Oil Pile, Cell No. 3

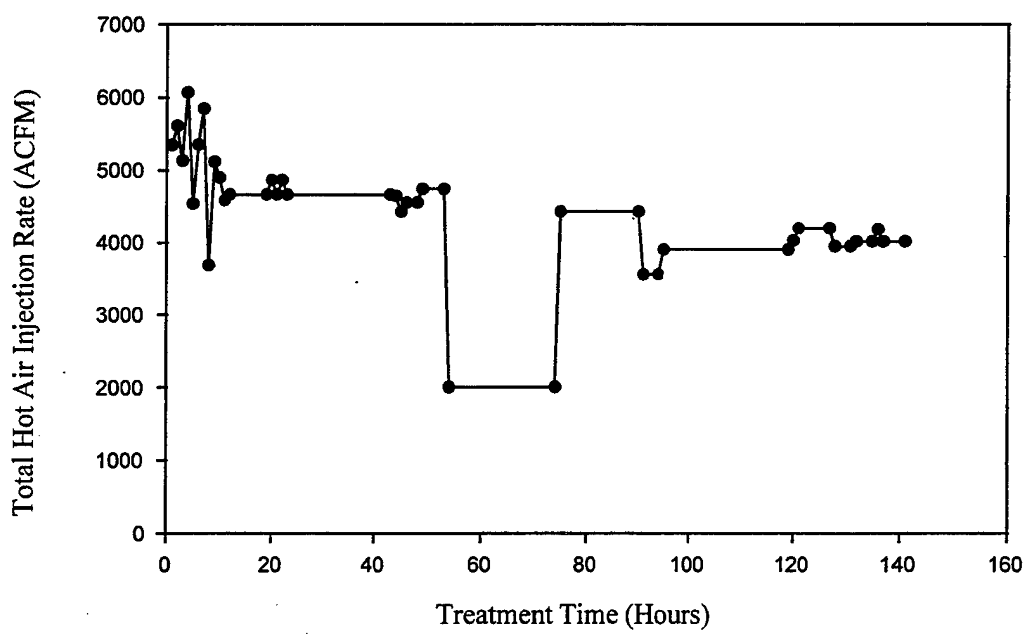


Figure 5-23. Total Air Flow Rate for Heavy Oil Soil Pile, Cell No. 3

as it was found to be capable of withstanding high temperatures, high winds, and abrasion.

The modified HAVE system design (Figure 4-3) with 18-inch spacing between injection levels was chosen for further demonstration studies to maintain uniform temperatures.

5.2.2.2 Run 4 - Remediation of Mixed Fuel Contaminated Soil Pile

The mixed fuel pile from low temperature HAVE treatment in Cell No. 2 was treated in the demonstration Run 4. As most of the low boiling petroleum fractions such as gasoline and some diesel were removed during Run 2, more than two-thirds of the contaminants left for treatment in Cell No. 4 was made up of heavy oil, lubricating oils, and heavier fractions. The clay content was the same at 19 percent, but the soil moisture content was reduced to 4.4 percent.

The modified HAVE system design was used for this run. The depth of soil between levels was reduced to 18 inches, and the constructed pile was shallower than that used in Run 2.

Pretreatment samples taken on September 27, 1995 indicated a TPH concentration of 5,807 ppm and contaminant distribution as indicated in Table 5-2. No other samples were taken prior to startup of operations for Run 4 due to budget limitations for additional analyses. The post-treatment TPH concentration of 171 ppm, and 38 ppm for diesel are well within the target remediation levels.

The main difference in the performance of the modified HAVE system is due to the ability to maintain higher soil temperatures with the new design. Soil temperatures at the end of the run ranged from 276°F to 460°F within the pile, and the average temperature in the four levels was over 400°F. The higher soil temperatures that could be maintained were sufficient to increase the vapor pressures of the high boiling fractions, and the released vapors were swept out with the air flow.

TPH and Soil Moisture

The treatment progress for Cell No. 4 was more uniform than for previous studies. Approximately 99 percent of the diesel fraction was removed at the end of treatment. The removal percentages were higher than 95 percent for all hydrocarbon fractions except the C30+, which had a 93 percent removal efficiency. Figures 5-24 and 5-25 show the contaminant distribution and TPH concentrations during treatment.

The soil moisture content during treatment is shown in Figure 5-26. Except for a short period between 90 and 150 hours, the soil moisture decreased uniformly throughout the treatment process. The high clay content of the soil, as noted before, may be a factor contributing this behavior. Figure 5-27 shows the direct relationship between TPH and soil moisture content.

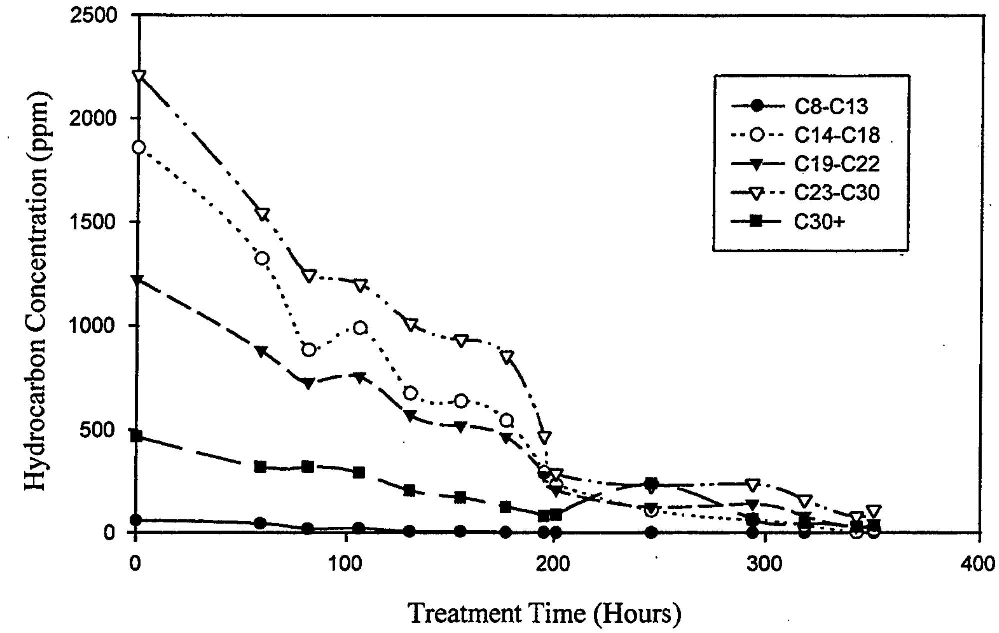


Figure 5-24. Contaminant Distribution for Mixed Fuel Soil Pile, Cell No. 4

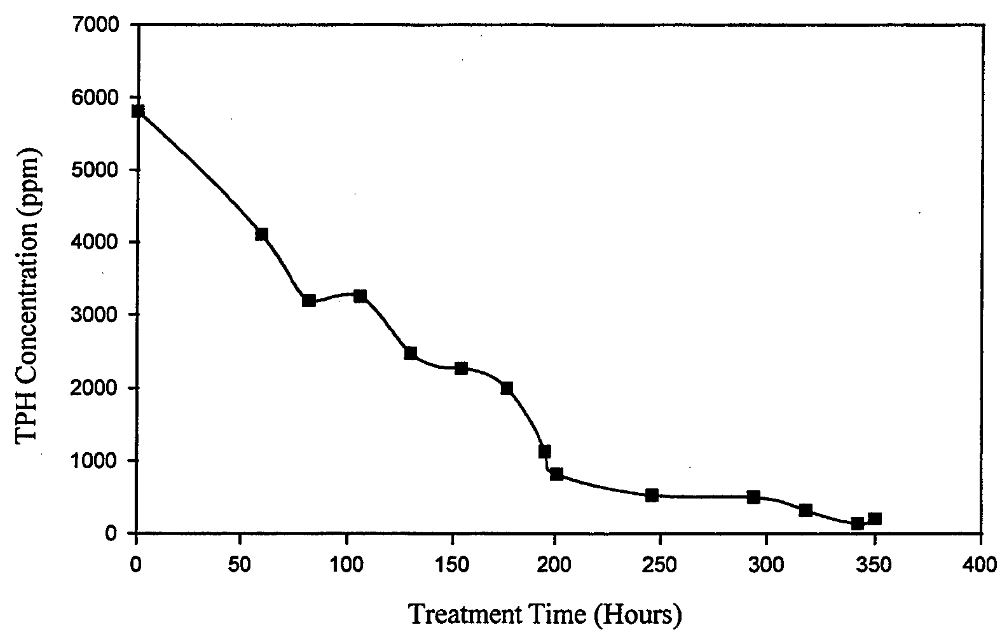


Figure 5-25. Treatment Progress for Mixed Fuel Soil Pile, Cell No. 4

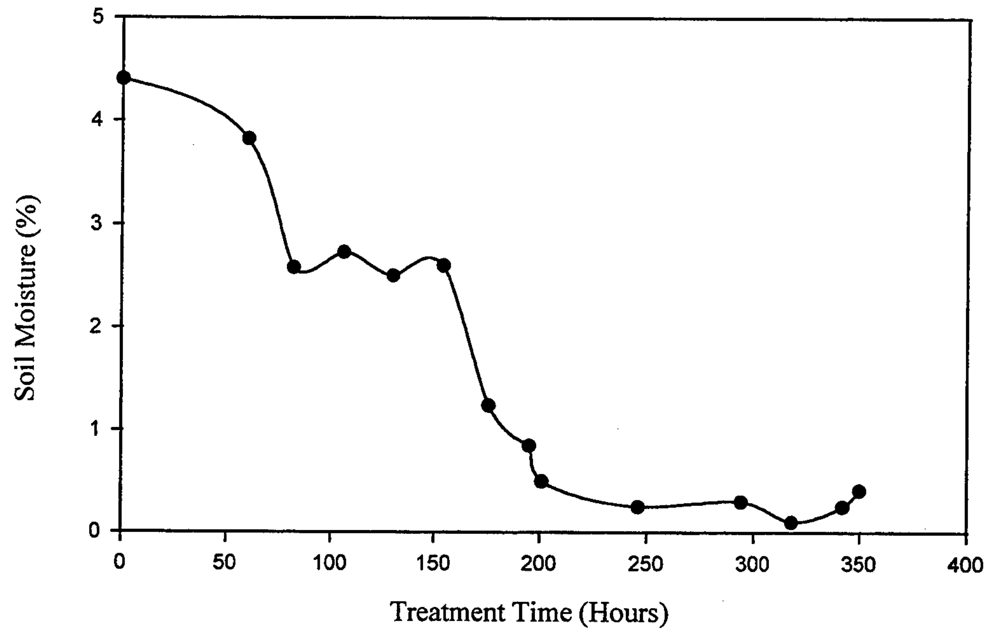


Figure 5-26. Soil Moisture Content for Cell No. 4

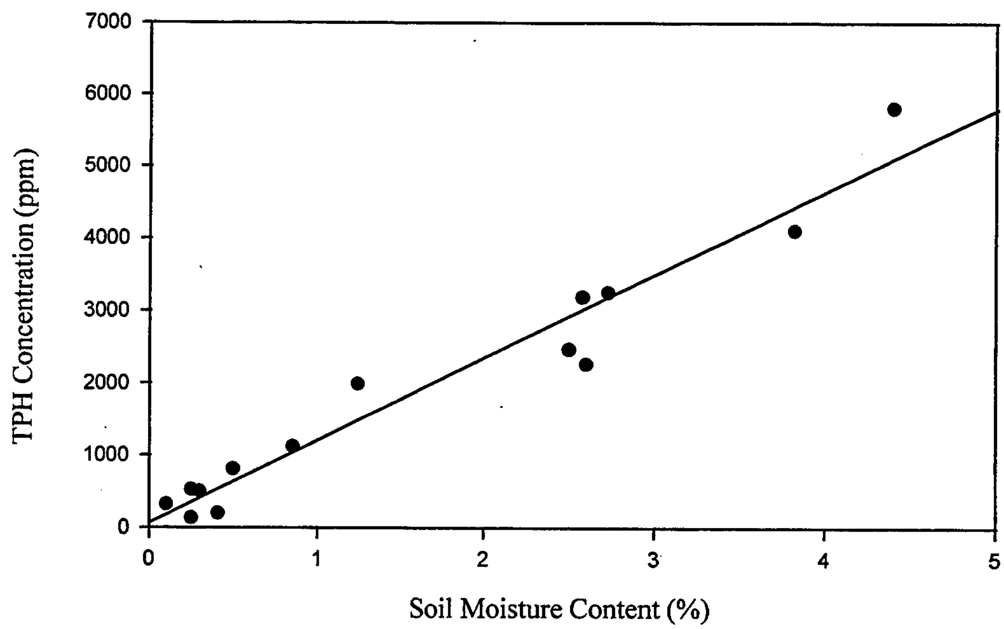


Figure 5-27. Soil Moisture and TPH Relationship for Cell No. 4

Soil Temperature

A total of 30 sensors were used to monitor temperature histories throughout the pile, at locations adjacent to the Level 1 and 3 hot air injection ducts, at the perimeter of the soil pile, and within the injection pipes. Due to the voluminous nature of the data collected, all of the temperature data are not included here. A summary of the findings is provided below.

The soil temperatures at mid-pile locations at 20-foot intervals in Level 1 and Level 2 are shown in Figures 5-28 and 5-29. The soil temperatures increased rapidly within 41 hours to over 200°F and remained steady at around 212°F until about 163 hours of operation. At this point the moisture content was reduced to about 1 percent, and thereafter the temperature climbed steadily to over 400°F. Soil temperatures at the end of the run ranged from 330°F to 420°F in Level 1, and from 440°F to 490°F in Level 2.

In Levels 3 and 4, the soil temperatures reached about 212°F after 45 hours and 60 hours of operation, respectively. The difference in heating times for each level is in part due to the adjustments made in the injection air flow rates to each level. The soil temperatures were nearly constant at 212°F until about 200 hours of operation, and thereafter steadily increased to over 400°F. The air flow rates were adjusted to increase flows to ducts 3 and 4 to provide more rapid heating. At the end of treatment, the temperatures ranged from 370°F to 420°F in Level 3, and 270°F to 440°F in Level 4. Figures 5-30 and 5-31 display temperature histories for Levels 3 and 4.

The soil temperatures measured using a cluster of thermocouples close to the Level 1 and 3 injection ducts showed substantial differences for the two levels due to the differences in air flow rates to the two levels. For Level 1, the temperature adjacent to the hot air duct increased from 300°F at 17 hours of operation to 450°F at 163 hours operation. In contrast, the temperature in Level 3 reached 300°F at 45 hours and remained at that value until 163 hours. Thereafter, due to an increase in flow rate to this level, the temperature steadily climbed to 450°F at the end of operation. The temperatures measured by the three sensors located 4 inches apart were about 100°F lower than that measured by the sensors close to the injection duct in each level. These data indicate that there is rapid convective heat and mass transfer to provide uniform temperatures when there is sufficient moisture in the soil.

Hot air injection temperatures were measured at both ends of the pipe within the pipe for ducts in all levels. The temperature was 600°F to 700°F in the Level 1 duct close to the manifold, and 500°F to 600°F at the other end of the pipe. The gradients along the width of the pile may be somewhat lower for the upper levels, though this data is not available due to malfunction of Sensor No.12. Two sensors (Nos. 13 and 20) located along the length of the pile in Level 2 recorded approximately the same temperatures, indicating a uniform temperature profile along the length of the bed. The lowest temperature was recorded in Level 3, at the farther end of the injection duct, where the temperatures ranged from 300°F to 500°F.

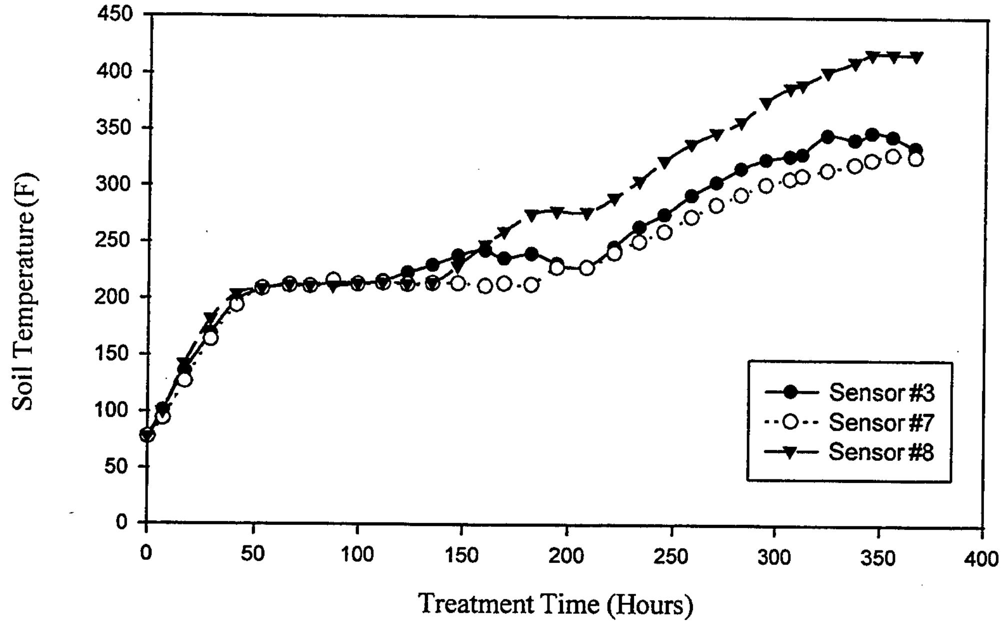


Figure 5-28. Level 1 Soil Temperature for Mixed Fuel Soil Pile, Cell No. 4

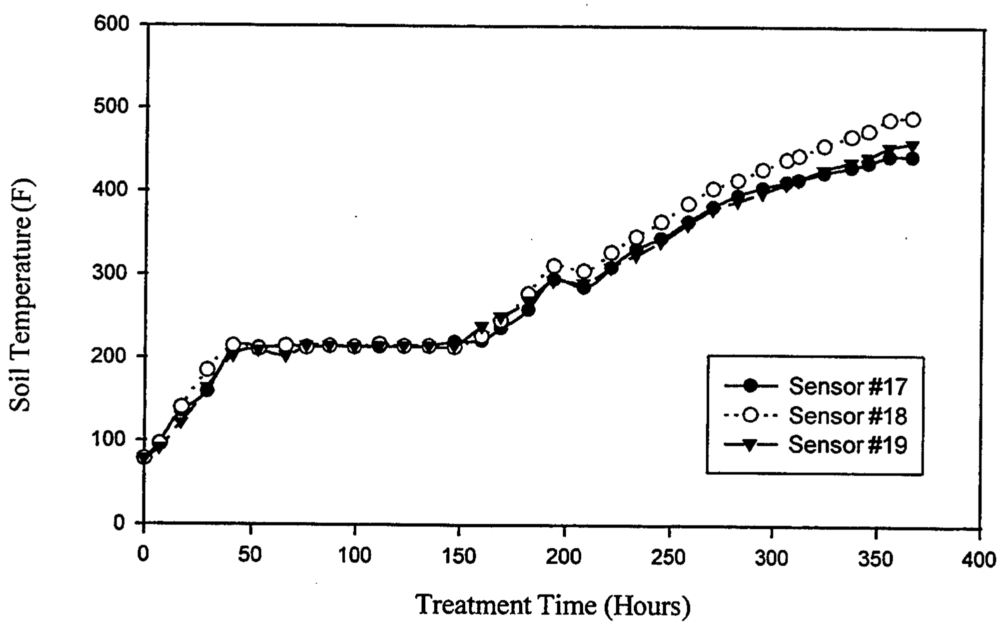


Figure 5-29. Level 2 Soil Temperature for Mixed Fuel Soil Pile, Cell No. 4

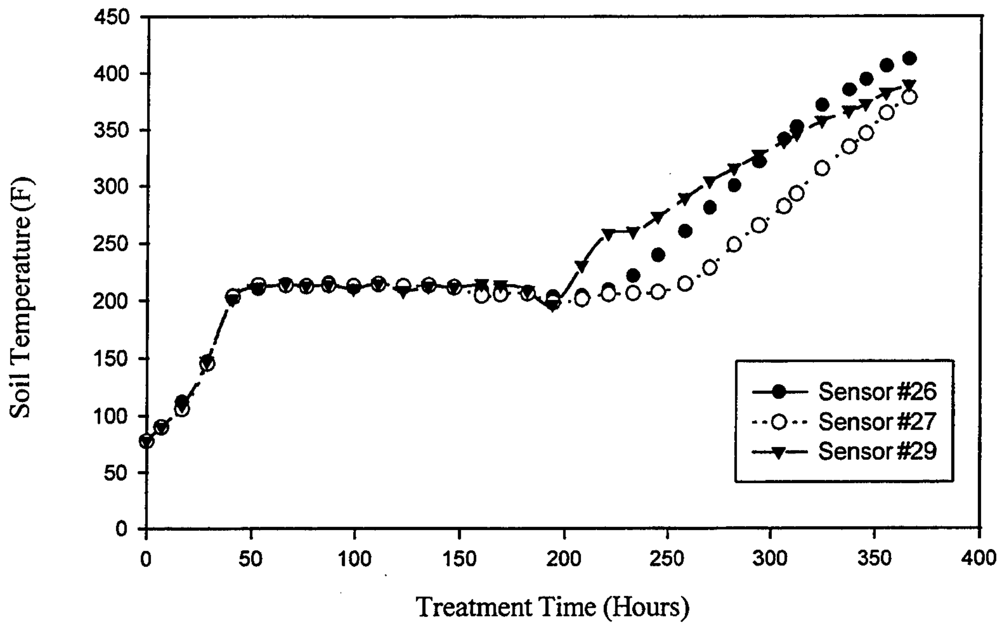


Figure 5-30. Level 3 Soil Temperatures for Mixed Fuel Soil Pile, Cell No. 4

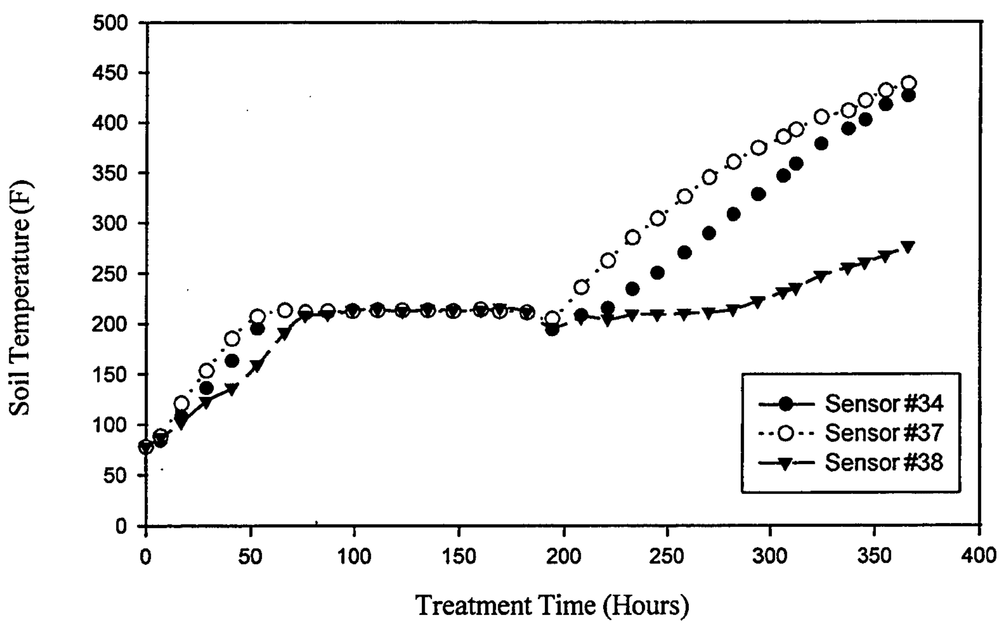


Figure 5-31. Level 4 Soil Temperatures for Mixed Fuel Soil Pile, Cell No. 4

Soil temperatures were also monitored at the pile perimeter in Levels 1 and 3. Sensor Nos. 6 and 10 are located on opposite ends along the width of the pile in Level 1. Sensor No. 6 is located 3 inches from the injection manifold, and sensor No. 10 is located 3 feet into the pile near the perimeter. Sensor Nos. 22 and 30 were installed in a similar manner in Level 3. The data from all sensors are within about 5°F of each other for about the first 150 hours of operation. When the moisture is depleted, and the temperature rises beyond 212°F, there is a difference of about 100°F between the sensors located at each level.

Process Improvements

The demonstration Run 4 successfully treated the soil to below target contaminant levels, and provided information for further optimization of treatment cell construction, operation, and performance monitoring. The following improvements were implemented for Run 5.

- High soil temperatures were attained in Cell No. 4 during the latter portion of the treatment period. The bottom soil level was increased by 6 inches to further insulate the underlying asphalt pad for Run 5.
- Vertical spacing between injection levels 2, 3, and 4 were maintained at 18 inches.
- Return air ducts were replaced to accept high vapor temperatures.
- Acrylic impregnated fiberglass sheeting was used for enclosing the soil pile.
- Air supply to the catalytic oxidizer was boosted by tapping combustion air.

5.2.2.3 Run 5 - Remediation of Mixed Fuel Contaminated Soil Pile

The mixed fuel contaminated soil treated in Cell No. 5 had approximately 73 percent of the contaminants in heavy oils, lubricating oils, and higher petroleum fractions. The soil moisture content at 11.5 percent was higher than in Run 4, but the clay content at 3 percent was much lower than the soil treated in Run 4. This matrix of parameters was conducive for successful HAVE system operation even though the soil was contaminated predominantly with high boiling petroleum fractions. The removal efficiency for the diesel fraction was over 99 percent, and for the C30+ fractions the removal efficiency was 93 percent. The main features of this demonstration are presented in the following sections.

TPH and Soil Moisture

The contaminant distribution during treatment, and the TPH concentration profile are shown in Figures 5-32 and 5-33. The concentration decrease with time for each petroleum fraction is almost linear indicating contaminant removal under uniform conditions. The contaminants and moisture appear to be readily available for removal, and not bound to the clay

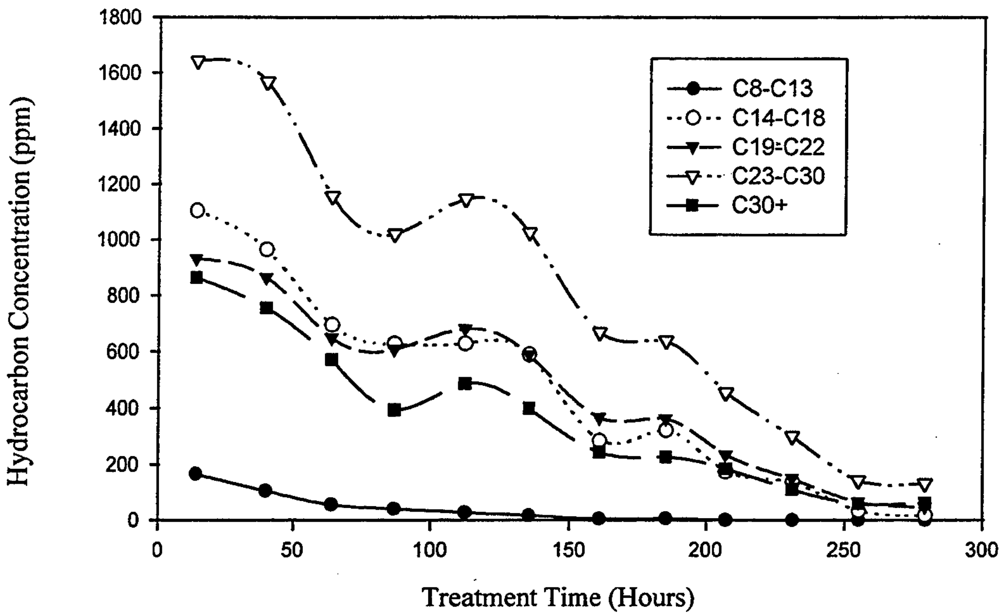


Figure 5-32. Contaminant Distribution for Mixed Fuel Soil Pile, Cell No. 5

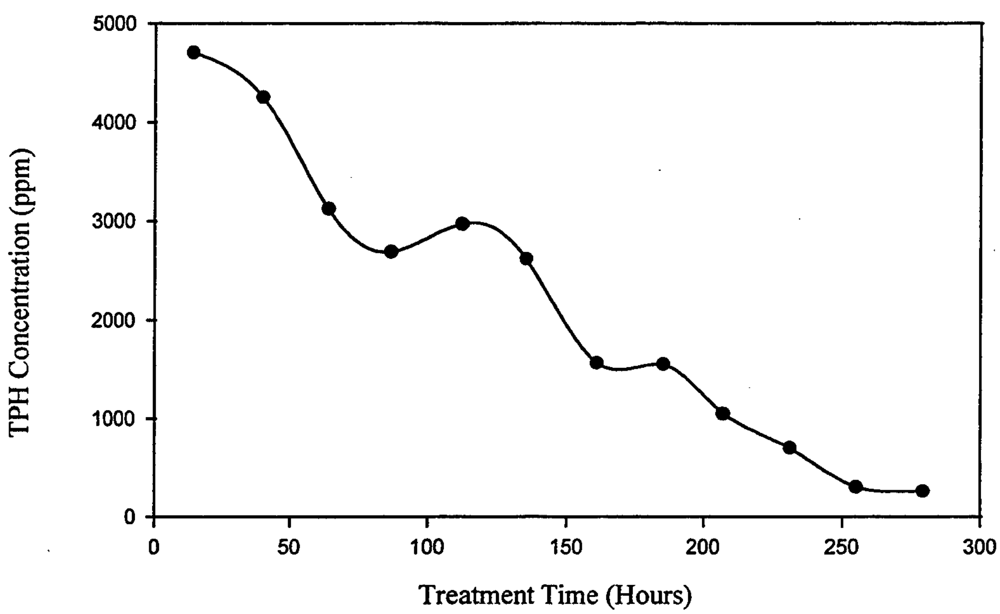


Figure 5-33. Treatment Progress for Mixed Fuel Soil Pile, Cell No. 5

in the pore structure as with soils containing high amounts of clay. There is no distinct plateau, as was the case with profiles for Cell No. 3 and 4. The TPH removal rate is also almost linear with time.

The soil moisture content during treatment is plotted in Figure 5-34, and displays a typical drying curve. During the first 70 hours rapid removal of free moisture takes place, and thereafter moisture removal occurs at a slower uniform rate. The relationship between TPH concentration and soil moisture content is linear as shown in Figure 5-35.

Soil Temperature

Temperature histories were obtained from 24 sensors located within the four levels of the soil pile, adjacent to the injection pipes, and within the injection pipes. The important features are presented in the following sections. The temperature was nearly uniform throughout the cell at around 200°F after the initial ramp phase. This constant condition lasted until about 210 hours or 75 percent of treatment duration. The high moisture content of 11.5 percent resulted in nearly uniform temperatures being maintained throughout the pile by evaporation, convective transfer, and condensation at cooler areas. During this period, more than 80 percent of the contaminants were removed, essentially by steam stripping. After the moisture content was reduced to about 2 percent, soil temperatures gradually increased and varied to some extent in different levels.

Soil temperatures at mid-pile in Levels 1 and 2 located at about 20-foot intervals are shown in Figures 5-36 and 5-37. The temperature increase was gradual after the initial heating phase of 30 hours in Level 1 and 45 hours in Level 2. The temperatures remained steady at around 200°F until about 210 hours of operation and were within 10°F at all sensor locations. In Level 2, the temperatures were within about 5°F at the two sensors located about 40 feet apart. These data indicate that the treatment cell construction was optimal in providing uniform heat transfer from the injected air to the soil. The high moisture content of the soil was an additional factor in providing rapid heat transfer by conduction and convection. Once the moisture level was reduced to about 2 percent, there was some variation in temperatures along the length of the pile, particularly in Level 1. The maximum difference was about 50°F at the end of treatment for sensor Nos. 4 and 12.

The soil temperatures at mid-pile in Levels 3 and 4 are shown in Figures 5-38 and 5-39. The temperature sensor No. 31 is located in the middle of the three sensors Nos. 31, 34, and 38. The sensors No. 31 and 34 are separated by 25 feet, and No. 31 and 38 are separated by about 40 feet. Figure 5-38 shows that the temperatures are uniform and within 5°F at these three widely separated locations after the initial heating phase to about 175 hours. After this point, the reduced moisture content and increased air supply to this level results in temperature variations. Figure 5-39 shows the temperature in Level 4 (No. 40), and in the injection duct (No. 41). The temperature at this level remained constant at around 200°F throughout the treatment.

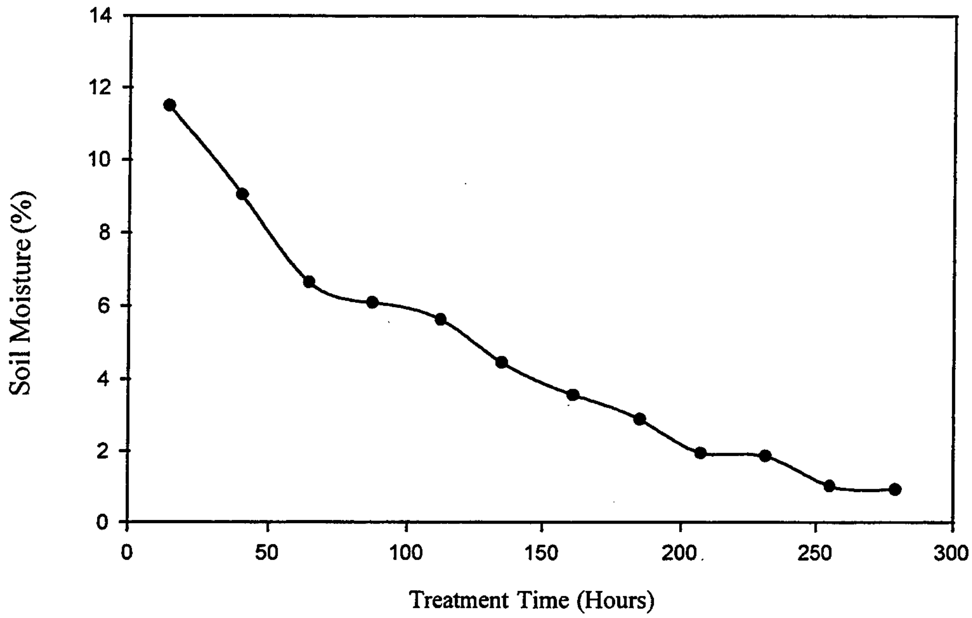


Figure 5-34. Soil Moisture Content for Cell No. 5

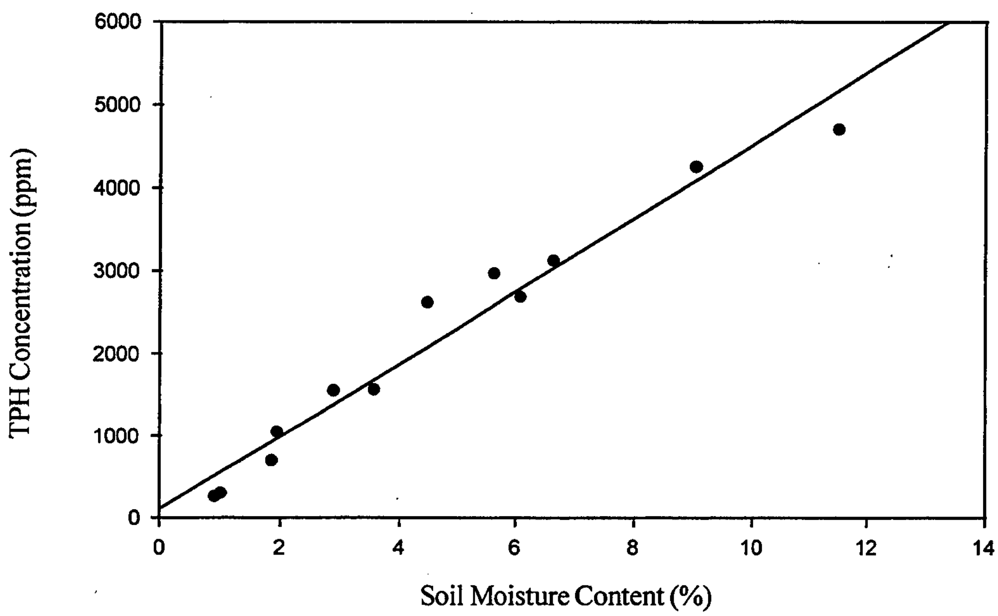


Figure 5-35. Soil Moisture and TPH Relationship for Mixed Fuel Soil Pile, Cell No. 5

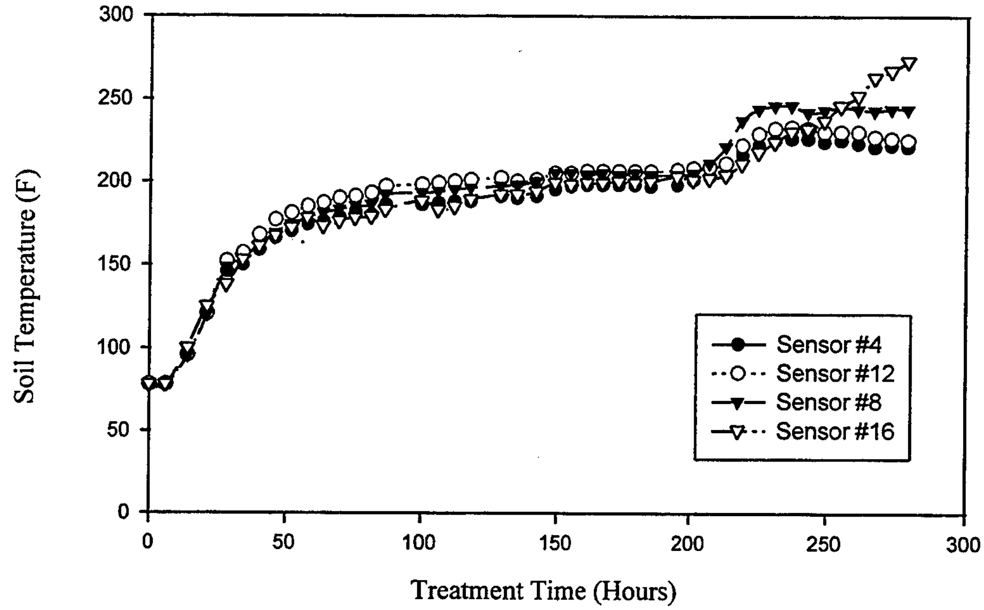


Figure 5-36. Level 1 Soil Temperatures for Mixed Fuel Soil Pile, Cell No. 5

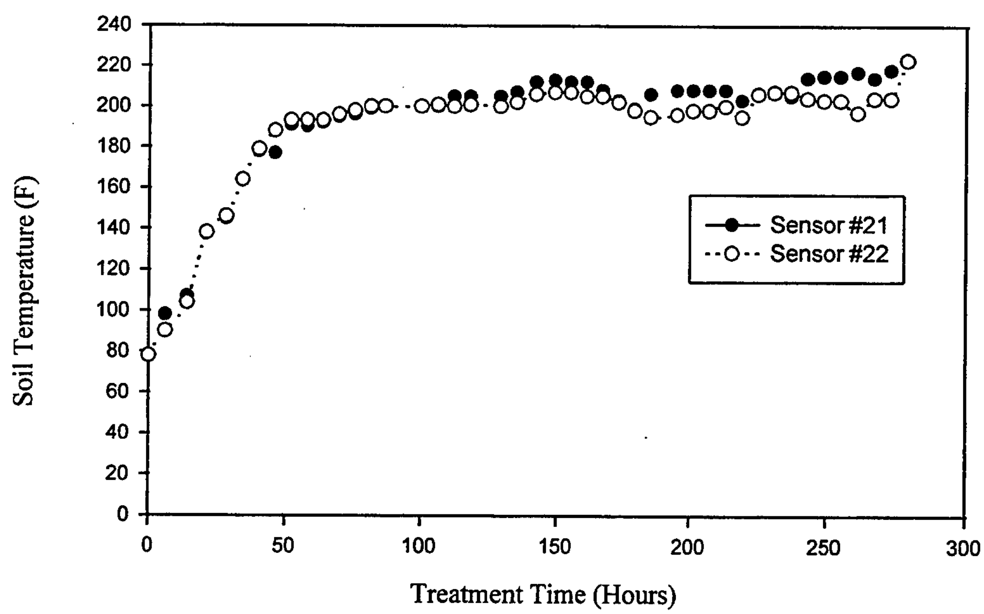


Figure 5-37. Level 2 Soil Temperatures for Mixed Fuel Soil Pile, Cell No. 5

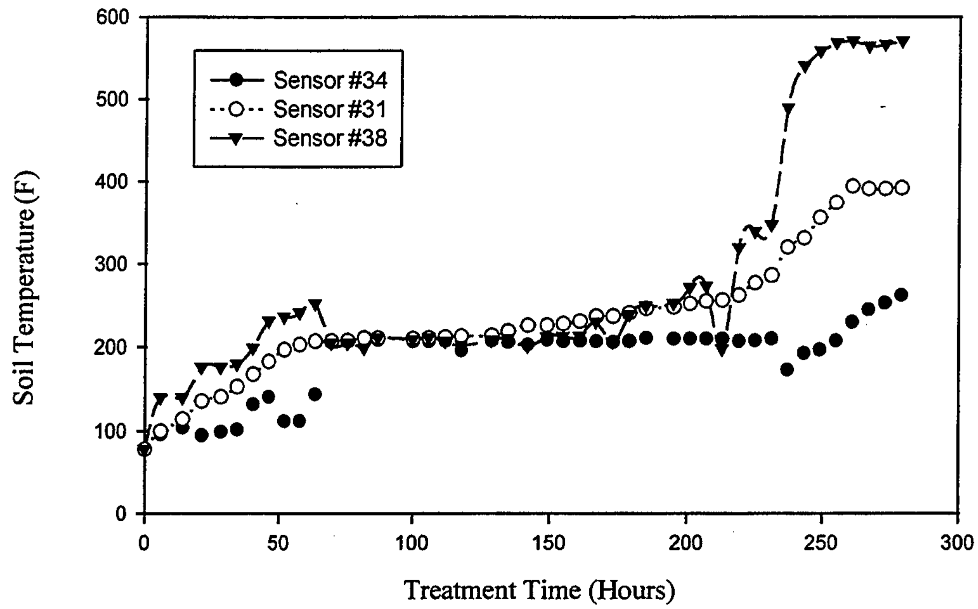


Figure 5-38. Level 3 Soil Temperatures for Mixed Fuel Soil Pile, Cell No. 5

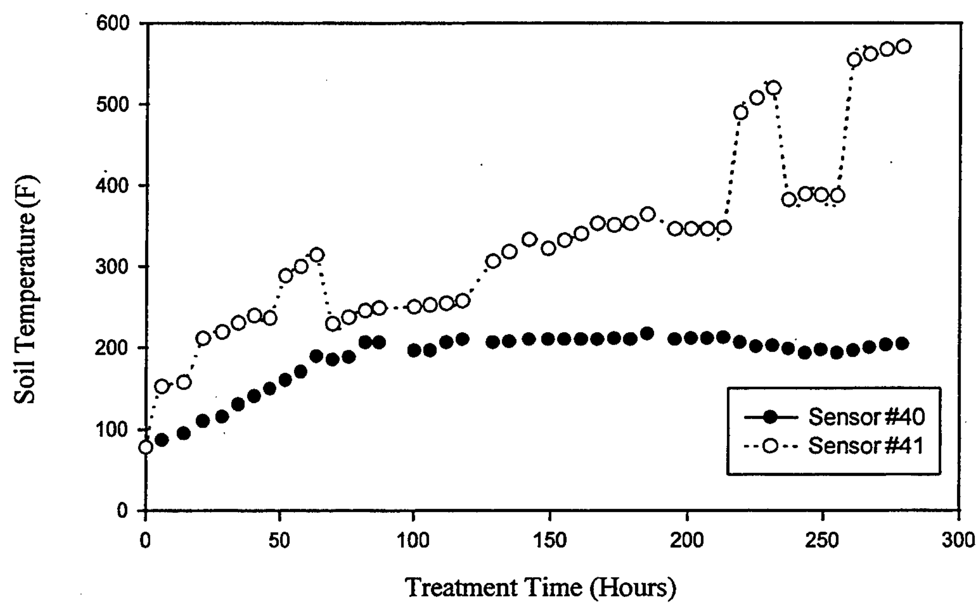


Figure 5-39. Level 4 Soil Temperatures for Mixed Fuel Soil Pile, Cell No. 5

The soil temperatures adjacent to the 4-inch duct in Level 1, and at distances of 4 and 8 inches from the duct, are shown in Figure 5-40. The temperatures were fairly close initially, but varied by about 100°F as the moisture level decreased. Toward the last 60 hours of operation when the air flow rates to this level were decreased, the temperatures were again same at all three sensor locations. The temperatures within the injection pipes are shown for each level in Figure 5-41. These data indicate that the pipe temperatures along the length of the pile are within about 20°F for levels 1, 2 and 3 (sensor Nos. 5, 6, 20, and 24). The temperatures increased from 300°F after 14 hours of operation to about 500°F at 210 hours. The pipe temperature (sensor No. 41) in Level 4 was lower by about 80°F due to the lower air flow rates to this level. The temperature increased to about 500°F after 213 hours of operation when air flow rates were increased to the Level 4 manifold, and decreased at the other levels.

This demonstration run has shown that the HAVE system can be operated to maintain uniform temperatures throughout the pile. Moreover, by using the dampers in the main injection duct to each level, it is possible to regulate the air flow, and hence the temperature at each level. The hydrocarbon concentrations and treatment progress at different locations were monitored in the field using thin layer chromatography (TLC). The HAVE system provides sufficient flexibility to fine tune the operation during treatment to increase or decrease air flows to different sections of the cell as determined by TLC analysis.

5.3 REMEDIATION EFFECTIVENESS

5.3.1 Remediation Efficiency

The HAVE system successfully remediated soils contaminated with low and high boiling petroleum hydrocarbons to reduce the TPH concentrations to regulatory standards, below 100 mg/kg gasoline and 250 mg/kg diesel. Low temperature operation was sufficient to treat gasoline contaminated soils, and resulted in 100 percent removal of contaminants. In the case of soils contaminated with significant amounts heavy oils, lubricating oils, and higher fractions, low temperature operation can not be expected to produce satisfactory results. The second demonstration was conducted at an average soil temperature of 150°F, and resulted in the removal of about 4,000 pounds of TPH. However, most of the contaminants removed were in the C4 to C12 range. The removal efficiency for this fraction was 100 percent, while those for the C13 to C23 and C23+ range were only 27 percent and 14 percent, respectively. The major factors affecting system performance in this case were:

- The matrix of parameters including contaminant type, clay content, and soil moisture content inhibited technology performance.

- In addition, the HAVE system design as used in Run 2 resulted in short-circuiting of injected air through interstitial space between the pile and the membrane to the vapor extraction ducts.

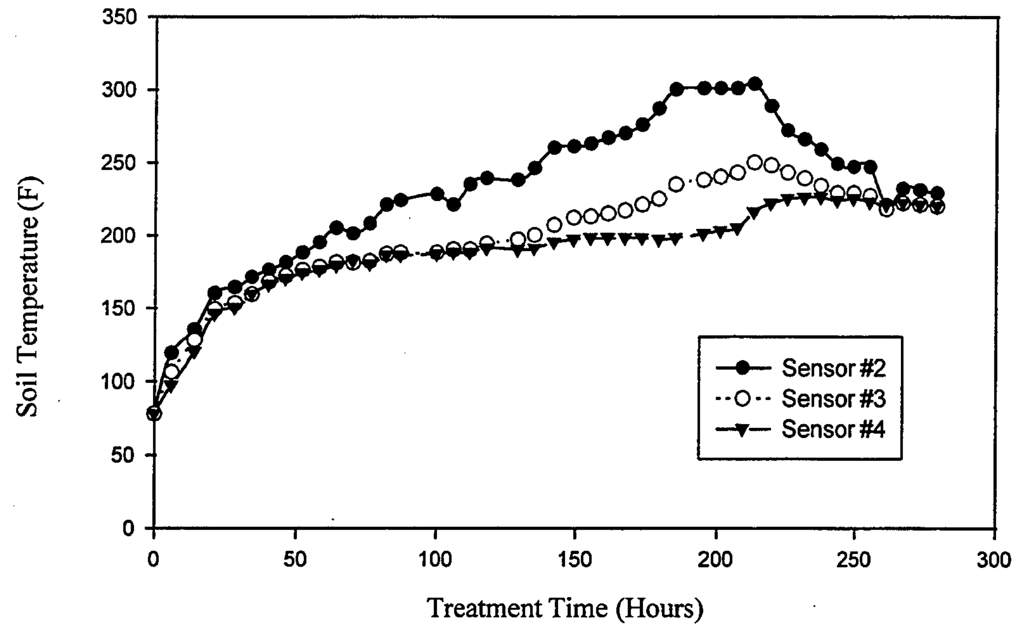


Figure 5-40. Soil Temperatures at 4-inch Spacing from Level 1 Injection Pipe for Cell No. 5

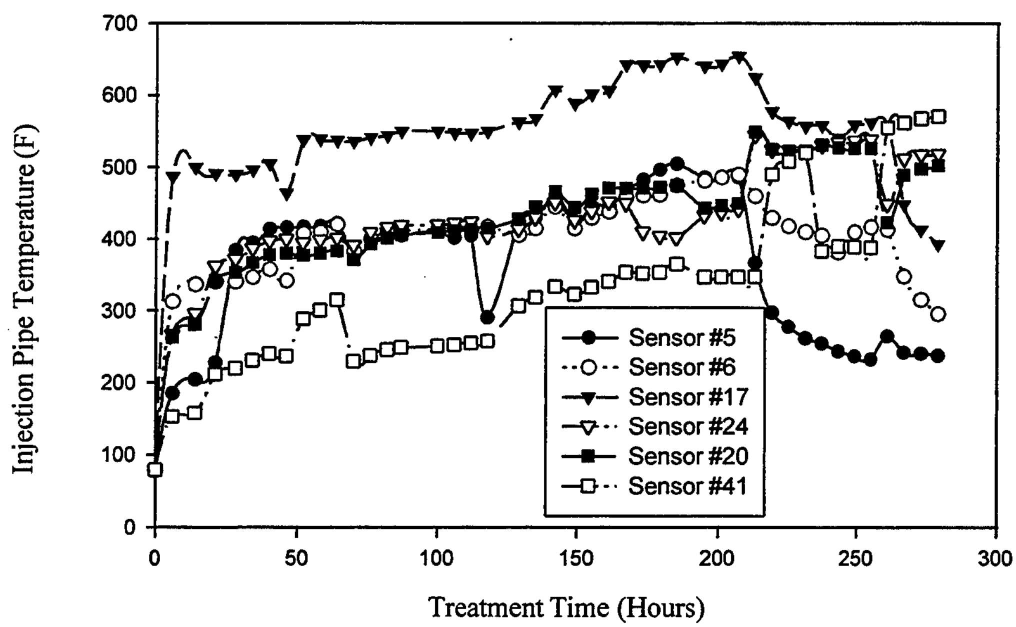


Figure 5-41. Injection Duct Temperatures for Mixed Fuel Soil Pile, Cell No. 5

- The 28-inch spacing between injection levels was too large to provide uniform heating in this case.

The modified HAVE system provided excellent removals for all ranges of hydrocarbons. In Run 3, TPH concentrations of heavy oil contaminated soils were reduced from 177 ppm to 40 ppm during 6 days of operation. The removal efficiencies were 100 percent and 92 percent, respectively for the C4 to C13 and C14 to C18 hydrocarbon range.

In Run 4, the matrix of parameters included contaminants that are predominantly in the high boiling range, and high clay content. The HAVE system provided excellent treatment by reducing TPH concentration by 97 percent over 14 days of operation. The performance was similar for Run 5, with a TPH removal efficiency of 95 percent. The removal efficiencies for individual petroleum fractions are shown in Table 5-8.

5.3.2 Energy Requirements

The energy usage for HAVE system operation stems mainly from the fuel used in combustion to produce hot air for remediation and destruction of the contaminants. Propane usage during operation was monitored using percent full indicators on the tank and replacement frequencies. It was not feasible to install an electric meter at the site to monitor power consumption. Hence, power calculations are based on the total power consumption of 15.0 horsepower for the furnace and air recirculation blowers, and on-site generator. The total propane usage and power consumption over the period of operation are presented in Table 5-9.

Also, the energy requirements normalized for the volume of soil treated and the amount of contaminants removed are shown in the Table. The data indicate that Run 5 was the most efficient in terms of propane used per cubic yard of soil treated and per ppm of contaminant removed.

5.4 SYSTEM (PROCESS FLOW) PERFORMANCE

5.4.1 Treatment Cell and Vapor Injection and Extraction System

The constructed treatment cells excluding the membrane fabric performed satisfactorily for the most part during Phase 1 demonstrations with the original HAVE system design. Subsidence of the soil due to high porosity during construction Cell No. 1 was a minor problem that was readily corrected. There were no problems in the construction of Cell Nos. 2 to 4. The need to increase the soil temperature to treat the mixed fuel soil pile (Run 2) exposed some system shortcomings with this design as noted below:

- Any attempts to increase flow rates resulted in leakage through the manifold injection pipe quick connect links in the front side wall of the cell.

- Attempts to increase injection air temperatures risked melting of the Canvex cover.

These limitations were overcome in the modified HAVE system design. Cell No. 5 provides the optimum design based on these demonstration runs. The membrane fabric used for covering the cell must be suitable to withstand interstitial temperature of the balloon and wind loads. The aluminized fiberglass used during Run 4 could not withstand the wind loads at the National Test Site. The acrylic fiberglass fabric used for Cell No. 5 provided uninterrupted system operation. However, the fabric must be carefully examined for degradation if it is to be reused for several remediations.

Table 5-8. Contaminant Removal Efficiencies (%)

Run	Gasoline C4 to C13	Diesel C14 to C18	Heavy Oils C19 to C22	Lube Oils C23 to C30	HF* C30+	TPH
3	100	92	61	71	76	77
4	100	99	97	95	93	97
5	100	98	95	92	93	95

* Heavier fractions.

Table 5-9. Energy Requirements

Run	Propane Used (gals)	Propane per cu. yd. Soil Treated	Propane per cu. yd. Soil per ppm Removed	Power Usage (Kw)	Power per cu. yd. Soil Treated	Power per cu. yd. Soil per ppm Removed
3	3,530	10.1	74.0 E-3*	1,600	4.6	34.0 E-3
4	9,850	20.5	3.6 E-3	3,920	8.2	1.46 E-3
5	7,000	13.4	3.0 E-3	3,120	6.0	1.34 E-3

* E-3 = 10^{-3}

5.4.2 Furnace, Blower and Catalytic Oxidation System

The mechanical and electrical components of the HAVE system functioned well during Runs 2, 3, and 5. System shutdown occurred shortly after startup for Run 1. This was due to furnace electrical wiring that came loose during transport and went undetected. During Run 4, the HAVE system was shut down for about 11 hours for repairs to the generator. The vapor blower and catalytic oxidation system did not have any malfunctions during the five runs.

5.4.3 Instrumentation

The instrumentation used for monitoring emissions and the temperature sensors performed as expected. The soil vapor monitor failed to provide steady readings, and the data could not be correlated with the laboratory data. Therefore, its use was discontinued. An 18-hour shutdown during Run No. 4 resulted from a burner control safety lockout. The lockout was the result of a malfunction in the pitot tube flow monitoring system for the combustion air supply line.

6.0 OTHER TECHNOLOGY ISSUES

This section covers demonstration considerations other than technology cost and technical performance. Regulatory requirements, personnel health and safety issues, and community acceptance issues all affect the degree of future success for any environmental remediation technology. These subjects are discussed below.

6.1 ENVIRONMENTAL REGULATORY REQUIREMENTS

This section discusses the regulatory requirements pertinent to site remediation using the HAVE technology to treat soil contaminated with petroleum hydrocarbons, such as diesel fuel or heavier fuel oils. Regulations applicable to a particular application of this technology will depend on site-specific conditions and the type of contaminated soil being treated.

Pretreatment and post-treatment soil sampling are required for the successful operation of the HAVE system. Any pretreatment or post-treatment process employed may have additional regulatory requirements that need to be determined prior to use. This section focuses on the regulations applicable to the HAVE system only.

6.1.1 Regional Water Quality Control Board (RWQCB)

In California, the application of HAVE technology to soils contaminated with petroleum hydrocarbons is generally regulated as a designated waste by either the RWQCB or the local county environmental health agency. For the application of the HAVE technology, soil cleanup levels will be the most significant regulatory permit condition imposed. Cleanup levels may be based on the nature of contamination, depth to groundwater, intended use of the treated soil, and/or the results of a site-specific risk assessment.

The application of cleanup levels to the remediation of petroleum hydrocarbon-contaminated soils in California is not uniform and varies county by county and agency by agency. At the Hydrocarbon National Test Site, located at CBC, Port Hueneme, the Regional Water Quality Control Board, Los Angeles Region (LARWQCB) has established the concentrations shown in Table 6-1 for reuse of the soils treated using the HAVE technology.

The LARWQCB permitted the CBC Port Hueneme HAVE system demonstration and issued the cleanup levels shown in Table 6-1 in the form of Waste Discharge Requirements (Order No. 93-007) and Monitoring and Reporting Program No. 7240. In addition to establishing cleanup levels, the LARWQCB required containment and diversion of storm water and quarterly sampling and reporting.

Table 6-1. HAVE Treatment System Cleanup Levels, LARWQCB

Parameter	Maximum Allowable Concentration (mg/kg)
TPH (gasoline range)	100
TPH (diesel range)	250
TPH (motor oil range)	1,000
Benzene	0.3
Toluene	0.3
Ethylbenzene	1.0
Xylene	1.0

6.1.2 Air Permitting

Air emissions may be regulated by the State and/or local air quality district. These may include fugitive emissions from the soil pile, exhaust emissions from the HAVE system, and emissions from soil excavation and transportation.

The demonstration of the HAVE system at the National Test Location was conducted under the Permit-to-Operate No. 7094, issued by the Ventura County Air Pollution Control District (VCAPCD). The permit imposed the following main conditions on the treatment system:

- Covering of the pile and weekly monitoring for fugitive emissions using a portable vapor analyzer
- Maintaining the combustion chamber at a temperature of 1,400°F or higher and a residence time of 0.5 seconds or longer
- Maximum allowable emissions at the outlet of the catalytic converter: 10 ppmv of ROC as hexane, 15 ppmv of NOx, and 10 ppmv of CO
- Weekly emission measurement of ROC, NOx, CO

In general, application of the HAVE system to treat soil contaminated with fuel hydrocarbons results in relatively low air emissions. The VCAPCD required weekly sampling of air emissions and quarterly reporting of the results. Eleven emission sampling events were conducted during the demonstration to fulfill requirements of the VCAPCD. Maximum field measured ROC emissions from the system were 8.2 ppmv as hexane during Test No. 4.

Average measured ROC emissions were 2.8 ppmv for all 5 test runs. Maximum field measured NOx emissions were 4.5 ppmv during Test No. 1. Maximum field measured CO emissions were 9.9 ppmv during Test No. 2. Average field measured concentrations of NOx and CO emissions were 1.6 ppmv and 5.3 ppmv, respectively, for all 5 test runs. The results of air emission monitoring are shown in Table 6-2.

Table 6-2. Emission Monitoring Results for Treatment Cells 1 Through 5

Cell No.	Date	Running Hours	Catalyst Flow (ACFM)	Catalyst Inlet Temp (°F)	Catalyst Outlet Temp (°F)	Furnace Chamber Temp (°F)	Exhaust - ppmv ROC	CO	NOx	Fugitive Emissions (ppm)
1	8/5/95	72	560	643	627	1640	2.2	8.6	4.5	<2.0
2	8/15/95	52	71	730	726	1600	0.8	3.4	0.2	<2.0
2	8/19/95	194	136	710	674	1550	1.5	9.9	0.8	<2.0
2	8/26/95	329	8	742	682	1600	0.1	1.0	0.1	<2.0
3	9/29/95	141	180	725	668	1550	0.1	4.1	2.8	<2.0
4	10/14/95	162	109	778	688	1500	1.7	1.9	0.4	<2.0
4	10/21/95	289	112	743	710	1550	7.5	0.9	1.5	<2.0
4	10/28/95	361	96	815	746	1600	8.2	6.3	0.9	<2.0
5	11/9/95	168	65	620	571	>1400	2.5	9	3	<2.0
5	11/16/95	278	40	750	707	>1400	4	5.3	1.5	<2.0
5	11/21/95	shut down	61	696	651	>1400	2	7.5	2.3	<2.0

6.1.3 Other State and Federal Regulatory Requirements

The HAVE system was used to treat petroleum hydrocarbon-contaminated soils that were characterized as nonhazardous under California and federal hazardous waste regulations. California hazardous waste regulations are contained in Title 22 of the California Code of Regulation (CCR), Division 4.5, Chapter 11.

The Resource Conservation and Recovery Act (RCRA), as amended by the Hazardous and Solid Waste Amendments of 1984, is the primary federal legislation governing hazardous waste activities. Subpart C of RCRA contains requirements for generation, transport, treatment, storage, and disposal of hazardous waste. Criteria for identifying hazardous wastes are included in Title 40 of the Code of Federal Regulations (CFR) Part 261.

Soils contaminated only with diesel or fuel oil petroleum hydrocarbons generally do not meet hazardous waste criteria unless they are also contaminated with other substances such as solvents, metals, or waste oil. In particular, RCRA Subtitle C provides an exclusion (40 CFR 261.4(b)(10)) from the toxicity characteristic for contaminated soils resulting from UST corrective action, which is regulated under RCRA Subtitle I (40 CFR 280). Application of the HAVE technology to hazardous wastes would require permitting by the California EPA Department of Toxic Substances Control (DTSC), or the Federal EPA.

The federal Clean Water Act (CWA) regulates direct discharges to surface water through National Pollutant Discharge Elimination System (NPDES) regulations. These regulations require point-source discharges of wastewater to meet established water quality standards. If wastewater is discharged to surface water bodies or publicly owned treatment works (POTWs), CWA regulations apply. On-site discharges to surface water bodies must meet substantive NPDES requirements, but do not require a NPDES permit. Off-site discharges to a surface water body require a NPDES permit and must meet the NPDES permit limits. Pretreatment standards apply to discharges to a POTW, which is considered an off-site activity, even if an on-site sewer is used. The operation of the HAVE system does not generate any wastewater or leachate water and therefore, it is not regulated by the CWA.

The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), as amended by the Superfund Amendments and Reauthorization Act (SARA) of 1986, provides an exclusion for petroleum hydrocarbons; therefore, CERCLA generally does not apply to the application of HAVE technology to sites contaminated only with petroleum hydrocarbons. However, the technology does meet CERCLA treatment standards by permanently and significantly reducing the volume and toxicity of contaminants.

Occupational Safety and Health Act (OSHA) regulations, contained in 29 CFR Parts 1900 through 1926, are designed to protect worker health and safety. A site-specific Health and Safety Plan was prepared for the HAVE technology demonstration and the plan met all applicable OSHA requirements. Major elements of the Health and Safety program for this demonstration include: identification of medical clinic for emergency services, health and safety training for field personnel, personal protective equipment for field operations, medical surveillance for site personnel, and air monitoring.

6.2 PERSONNEL AND HEALTH AND SAFETY

Personnel requirements for operation and maintenance of the HAVE system are minimal. Generally, the HAVE system is operated during two 12-hour shifts, 7 days a week for a continuous system operation. The system is operated by one operator per shift. In addition, a field supervisor is needed who will provide supervision, communicate with the regulators, and provide technical support for field operations. The field supervisor must be on-site part time, and be available for on-call duty 24 hours a day. The typical routine tasks needed to be performed by field personnel are as follows:

- Collecting measurements from the following types of equipment: velocity meter/pitot tube, gas chromatograph - flame ionization detector (FID), PhD2 gas monitor, thin layer chromatograph (TLC), and magnahelic meter

- Adjusting blower flow rates to achieve balanced flow rates in the system
- Troubleshooting minor operational problems
- Collecting soil samples for off-site analyses

The unit operators completed an OSHA initial 40-hour health and safety training course and an annual 8-hour refresher course before operating the HAVE system. The operators also participated in a medical monitoring program as specified under OSHA requirements. Managers or supervisors of personnel have completed an additional 8 hours of management health and safety training.

Potential hazards associated with the treatment system operation and monitoring include rotating machinery, heat stress, fire or explosion, physical exertion, and electrical and chemical exposures. Personal protective equipment required for operators included hard hats, ear plugs, chemically resistant steel-toed boots, safety goggles and glasses, chemically resistant gloves for handling petroleum hydrocarbon-contaminated soils, and (as applicable) National Institute of Occupational Safety and Health (NIOSH) or Mine Safety and Health Administration (MSHA)-approved disposable dust respirators equipped with exhalation valves rated for fumes and mists.

The potential hazards of the HAVE system operation and the procedures to ensure the health and safety of workers are described in the site-specific health and safety plan.

6.3 COMMUNITY ACCEPTANCE

The system has positive and negative impacts related to community acceptance. One positive impact is that contaminants are permanently destroyed and not transferred to another medium. Potential negative impacts include volatile air emissions, dust emissions, noise, and traffic.

Emissions of volatile contaminants are minimal due to the catalytic converter installed at the exhaust of the system. Dust impacts are minimal during construction and nonexistent following the installation of the soil pile covers. Noise impacts are generally minimal during construction and negligible during operation. Traffic impacts are minimized because off-site trucking activities are reduced compared to off-site treatment or disposal.

7.0 COST EVALUATION

The purpose of this economic analysis is to estimate costs for Hot Air Vapor Extraction System technology for use in full scale cleanup of petroleum contaminated soils across DoD sites. Two cases are considered, each with a project size of 750 cu. yds. The analysis is based on treating the soils to achieve a target remediation level of 250 ppm for diesel range and 1,000 ppm for motor oil range.

In Case 1, the soil is assumed to contain contaminants principally in the diesel and fuel oil range (C14 to C18) with moderate amounts of clay, and moisture content. In the second case the contaminants include, in addition, up to about 30 percent heavy oils (C18 to C22). For both cases the TPH concentration is assumed to be about 5,000 ppm.

Cost estimates presented in this section are based primarily on data compiled during the SERDP demonstration at the Hydrocarbon National Test Site, Port Hueneme, California. Costs have been placed in the Hazardous, Toxic, Radioactive Waste (HTRW) Remedial Action Work Breakdown categories applicable to HTRW remedial action activities at Superfund and RCRA sites. The RA-WBS level 1 (federal action) number for all these activities is 33. Twenty level 2, or project phase, cost categories are used to separate demonstration costs under federal action number 33.

The RA-WBS system hierarchy has four levels of detail as follows:

- Level 1: Federal Action, in this case Remedial Action, 33
- Level 2: Pre-, post-, and demonstration operations (20 categories, see bulletized list below)
- Level 3: Subtasks pre-, post- and demonstration operations
- Level 4: Subtasks pre-, post- and demonstration operations
- Level 5: Subtask elements primarily for demonstration operations (distinguishes portable versus permanent treatment units)

Each RA-WBS level adds more detailed cost information. Table 7-1 presents a summary of costs for the RA-WBS level 2 demonstration categories used for Case 1 and Case 2. Section 7.1 describes the details in each of these 21 categories. Costs are presented in January 1996 dollars and are considered to be order of magnitude estimates with an accuracy of plus or minus 20 percent.

7.1 BASIS OF COST ANALYSIS

A number of factors affect the estimated cost of treating soils contaminated with petroleum hydrocarbons. These include factors specific to the contaminated soil to be remediated, and site specific factors. The contaminant type, soil moisture content, and clay content are primary variables that will affect treatment costs. The volume of soil to be treated, treatment goals, accessibility of site, availability of utilities, and geographic location are some of the other key factors influencing the overall remediation costs.

Table 7-1. Summary Costs for Case 1 and Case 2

Account #	Item Description	Dollar Amount Case 1	Dollar Amount Case 2
33.01	Mobilization and Preparatory	$4,790	$4,790
33.02	Monitoring, Sampling, Testing, and Analysis	$9,290	$9,550
33.03	Site Work	0	0
33.11	Biological Treatment	0	0
33.12	Chemical Treatment	0	0
33.13	Physical Treatment	0	0
33.14	Thermal Treatment	$45,120	$47,955
33.15	Stabilization/Fixation/ Encapsulation	0	0
33.17	Decontamination and Decommissioning	0	0
33.19	Disposal (commercial)	0	0
33.20	Site Restoration	0	0
33.21	Demobilization	0	0
33.99	Distributive Costs	$7,190	$8,390
TOTAL		$66,390	$70,685

This analysis evaluates the effects of two contaminant types on overall project cost. Other factors, such as clay and moisture content, may also affect treatment duration or efficiency and hence project costs. However, based on results from Runs 4 and 5, it is anticipated that a higher temperature of operation may be used to obtain the same treatment with marginal increase in overall costs.

For both cases, this analysis assumes that the HAVE technology will treat contaminated soil in single 750 cu. yd. batches on a 24-hour per day, 7-day per week continuous operating schedule, until treatment is complete. The HAVE system design can be modified to accommodate batches that are smaller than the standard 750 cu. yd. treatment cell configuration. Larger volumes of soil can be treated in multiple batches of 750-cu. yd. volume.

Further assumptions about the site, the contaminated soil, and treatment which can affect cost for each case include the following:

- No uncharacterized contaminants exist in the soil.
- Soil does not contain significant amounts of heavy oil, lubricating oil, and heavier fractions.
- Soil does not contain chlorinated organic contaminants or metals that may volatilize during treatment.
- Treated soil will be disposed by the client.

This analysis assumes that the soil to be remediated is stockpiled adjacent to the treatment area and is readily available for continuous operation of several batches without supply interruptions. Sizes less than 750 cu. yds. can be expected to incur increased treatment costs of about 10 percent to 20 percent per cu. yd. The treatment costs are based on applicable local and state requirements for total petroleum hydrocarbons in the State of California. The demonstration runs indicate that the HAVE system technology can meet the target remediation levels for the State of California. The following assumptions were also made for each case in this analysis:

- Road access is readily available to the site for transportation of the HAVE system and other equipment to the site.
- Gas, electricity, and water lines are available for ready connection to the HAVE equipment.
- Fencing around the staging area and concrete barriers around propane tanks will be provided by the client.
- Air emissions from the HAVE system catalytic oxidation unit will be monitored by the HAVE system operators.
- Pretreatment and post-treatment soil sampling and analyses will be conducted by the client.
- Performance of the treatment system will be monitored using thin layer chromatography (TLC) by the HAVE system operators.

- Project management and consultation for any equipment malfunction and repairs are included in the estimated project costs.

For Cases 1 and 2, one soil sample each per 50 cu. yds. is to obtained for fuel fingerprint analysis. A minimum of 15 pretreatment and 15 post-treatment samples are to be analyzed to determine if target remediation levels have been achieved.

For both Cases 1 and 2, the thermal treatment duration and temperature required are based on demonstration Runs 4 and 5. The soil used in Run 4 had higher amounts of clay and a lower moisture content than for Run 5. The soil temperature at the end of remediation was 410°F for Run 4 and 310°F for Run 5. The required treatment duration was estimated based on time required for 95 percent removal of up to C18 hydrocarbons for Case 1, and up to C22 hydrocarbons for Case 2. Based on these demonstrations, the HAVE system operating conditions assumed for Case 1 for treating a 750-cu. yd. soil pile include the following:

- TPH concentration in soil of 5,000 ppm
- Thermal treatment duration of 12 days
- Average soil temperature at the end of treatment of 310°F to 410°F
- Mobilization, setup, and decommissioning period of 6 days

For Case 2, the HAVE system operating conditions assumed for a 750-cu. yd. soil sample include the following:

- TPH concentration in soil of 5,000 ppm
- Thermal treatment duration of 14 days
- Average soil temperature at the end of treatment of 310°F to 410°F
- Mobilization, setup, and decommissioning period of 6 days

7.2 COST CATEGORIES

Cost data associated with the HAVE technology have been assigned to the following 20 RA-WBS categories which fall under the HTRW Remedial Action Account, 33:

PRE-DEMONSTRATION COST ELEMENTS

- (33.01) Mobilization and Preparatory Work
- (33.02) Monitoring, Sampling, Testing, and Analysis (pre-, post-, and demonstration sampling analysis are included in this category, unlike full scale cleanup projects)[1]
- (33.03) Site Work

1 Because the HTRW RA-WBS system was designed for full scale cleanup/construction projects, and not demonstration projects, we have added post-demonstration and demonstration sampling and analysis to 33.02. This additional sampling is essential for a demonstration validation and would not be part of a full scale cleanup activity.

- (33.05) Surface Water Collection and Control
- (33.06) Groundwater Collection and Control
- (33.07) Air Pollution/Gas Collection and Control
- (33.08) Solids Collection and Containment
- (33.09) Liquids/Sediments/Sludges Collection and Containment
- (33.10) Drums/Tanks/Structures/Misc. Demolition and Removal

DEMONSTRATION COST ELEMENTS

- (33.11) Biological Treatment
- (33.12) Chemical Treatment
- (33.13) Physical Treatment
- (33.14) Thermal Treatment
- (33.15) Stabilization/Fixation/Encapsulation

POST-DEMONSTRATION COST ELEMENTS

- (33.17) Decontamination and Decommissioning
- (33.18) Disposal (other than commercial)
- (33.19) Disposal (commercial)
- (33.20) Site Restoration
- (33.21) Demobilization (includes reporting)
- (33.9x) User Defined (replace "x" with numbers 0-8)
- (33.99) Distributive Costs

The HTRW RA-WBS Data Dictionary defines the Level 2 categories (33.01 through 33.21). Categories 90 to 99 require additional discussion. Categories 90 to 98 allow flexibility to add or modify unique elements at Levels 2, 3, 4 and 5.

Categories 33.99, Distributive Costs are costs that cannot be attributed to any specific RA-WBS activity, but apply to the whole project. Examples of Distributive Costs at RA-WBS Level 3 are:

- (33.99.01) Supervision/Management (33.99.02) Administration
- (33.99.03) Office Management (33.99.04) Engineering
- (33.99.05) Purchasing & Construction Services
- (33.99.06) Security
- (33.99.07) Equipment Maintenance & Motor Pool
- (33.99.08) Temporary Construction Facilities
- (33.99.09) Utilities - Operation/Maintenance
- (33.99.10) Facility Operations
- (33.99.11) Operating Supplies/Services
- (33.99.12) Computer & Data Processing

- (33.99.13) Vehicles for Personnel
- (33.99.14) Winterization
- (33.99.15) Health & Safety
- (33.99.16) Miscellaneous Costs
- (33.99.17) Insurance Premiums
- (33.99.18) Money Costs
- (33.99.19) Home Office Costs

Each task and subtask has certain repeating elements such as: labor, capital equipment costs, materials, and subcontractor costs. These are not typically identified separately at the RA-WBS level, but are considered as part of each RA-WBS activity, or cost element.

Costs associated with each Level 2 category are discussed in the sections that follow. Costs for Category 33.14, Thermal Treatment, are also presented to the fifth level of detail in Section 7.2.4. If applicable, differences between the costs of Case 1 and Case 2 are then discussed. Some categories end with a summary of the significant costs within that category.

7.2.1. Mobilization and Preparatory Work (33.01)

Mobilization and Preparatory Work includes all preparatory work required to commence demonstration/construction. This includes: mobilization of demonstration equipment and facilities; mobilization of personnel; preconstruction submittal (i.e., Work Plan preparation and regulatory submittal such as EAs); setup/construction of temporary facilities; temporary utilities; temporary relocations; and setup of decontamination facilities and demonstration plant.

Mobilization costs consisted of preparation of Management Plan and Health and Safety Plan. The total associated costs are listed separately for Case 1 and Case 2.

7.2.2 Monitoring, Sampling, Testing, and Analysis (33.02)

The costs associated with pretreatment and post-treatment soil sampling, shipping samples, and analysis for TPH and moisture by off-site laboratories are included in this category. Monitoring of treatment progress using TLC analysis of soil samples is also included.

7.2.3 Site Work (33.03)

Site work consists of site preparation, site improvements, and site utilities. Site preparation includes demolition, clearing, and earthwork. Site improvements include roads, parking, curbs, gutters, walks, and other landscaping. Site utilities include water, sewer, gas, and other utility distribution. All work involving contaminated or hazardous material is excluded from this cost element. Storm drainage involving contaminated surface water is included under "Surface Water Collection and Control" (33.05). Note that topsoil, seeding, landscaping, and reestablishment of existing structures altered during remediation activities are included in "Site

Restoration" (33.20).

A fenced National Test Site with all the improvements was available for this for demonstration. Thus, no costs are included for this element. Site work costs for implementation of this technology is estimated to range from 5 percent to 7 percent of project costs for large to small projects.

7.2.4 Thermal Treatment (33.14)

Thermal treatment destroys toxic elements through exposure to high temperature in combustion chambers and energy recovery devices. This cost element includes the process equipment and chemicals required for treatment. Transportation costs are included in "Transport to Treatment Plant" (33.05.11, 33.06.08, 33.08.03, 33.09.04)

Thermal treatment costs consist of labor, materials, and equipment to construct the treatment cells, costs of licensing and leasing the HAVE technology and equipment, mobilization and setup costs, and operating costs. The mobilization and setup costs include the costs for transporting the equipment to the site, and labor and construction equipment costs for constructing the cell, and HAVE system equipment setup. These costs are shown in Tables 7-2 and 7-3 for Cases 1 and 2.

7.2.5 Decontamination and Decommissioning (33.17)

Decontamination and Decommissioning includes all activities associated with shutdown and final cleanup of a hazardous materials-related facility. This cost category includes: facility shutdown and dismantling activities, preparation of decommissioning plans, procurement of equipment and materials, research and development, and, for nuclear facilities, spent fuel handling.

Decommissioning costs for thermal treatment using HAVE technology consisted of removal and disposal of soil liners, vapor barrier membrane fabric, and associated materials. These costs are already included in the demobilization costs for thermal treatment.

7.2.6 Distributive Costs (33.99)

Distributive costs consist of project and construction management, engineering, purchasing, and health and safety.

Table 7-2. Cost for Thermal Treatment, Case 1

Account No.	Item Description	Unit of Measure	No. of Units	Dollar Amount
33.14.07	Hot Air Vapor Extraction	Lump sum		
33.14.07.01	Portable Unit - License and Lease	Lump sum	1	$9,750
33.14.07.01.01.	Solids Preparation & Handling			
	Loading/unloading	Cubic Yard	0	0
	Screening	Cubic Yard	0	0
	Grinding	Cubic Yard	0	0
	Pulverizing	Cubic Yard	0	0
	Mixing	Cubic Yard	0	0
	Moisture control	Cubic Yard	0	0
	Placement/disposal	Cubic Yard	0	0
33.14.07.01.02	Vapor Containment			
	Acrylic fiberglass fabric	Lump sum	1	$1,170
33.14.07.01.03	Liquid Preparation & Handling			
	Collection & Storage	Gallon	0	0
	Separation	Gallon	0	0
	Treatment	Gallon	0	0
	Release/disposal	Gallon	0	0
33.14.07.01.04	Pads/Foundation/Spill Control	Lump sum	1	$5,900
33.14.07.01.05	Mobilization/Setup	Lump sum	1	$8,300
33.14.07.01.06	Startup/Testing/Permits	Lump sum	1	$6,800
33.14.07.01.07	Training	Lump sum	0	0
33.14.07.01.08	Operation (short term)			
	Labor	Lump sum	1	$5,760
	Chemicals and raw materials	Lump sum	0	0
	Fuels and utilities	Lump sum	1	$4,630
	Maintenance & Repair	Lump sum	1	$1,020
33.14.07.01.10	Cost of Ownership	Lump sum	0	0
33.14.07.01.11	Dismantling	Lump sum	0	0
33.14.07.01.12	Demobilization	Lump sum	1	$1,790
TOTAL				$45,120

Table 7-3. Cost for Thermal Treatment, Case 2

Account No.	Item Description	Unit Of Measure	Number Of Units	Dollar Amount
33.14.07	Hot Air Vapor Extraction	Lump sum		
33.14.07.01	Portable Unit - License and Lease	Lump sum	1	$11,375
33.14.07.01.01	Solids Preparation & Handling			
	Loading/unloading	Cubic Yard	0	0
	Screening	Cubic Yard	0	0
	Grinding	Cubic Yard	0	0
	Pulverizing	Cubic Yard	0	0
	Mixing	Cubic Yard	0	0
	Moisture control	Cubic Yard	0	0
	Placement/disposal	Cubic Yard	0	0
33.14.07.01.02	Vapor Containment Acrylic fiberglass fabric	Lump sum	1	$1,170
33.14.07.01.03	Liquid Preparation & Handling			
	Collection & Storage	Gallon	0	0
	Separation	Gallon	0	0
	Treatment	Gallon	0	0
	Release/disposal	Gallon	0	0
33.14.07.01.04	Pads/Foundation/Spill Control	Lump sum	1	$5,900
33.14.07.01.05	Mobilization/Setup	Lump sum	1	$8,300
33.14.07.01.06	Startup/Testing/Permits	Lump sum	1	$6,800
33.14.07.01.07	Training	Lump sum	0	0
33.14.07.01.08	Operation (short term)			
	Labor	Lump sum	1	$6,140
	Chemicals and raw materials	Lump sum	0	0
	Fuels and utilities	Lump sum	1	$5,400
	Maintenance & Repair	Lump sum	1	$1,080
33.14.07.01.10	Cost of Ownership	Lump sum	0	0
33.14.07.01.11	Dismantling	Lump sum	0	0
33.14.07.01.12	Demobilization	Lump sum	1	$1,790
TOTAL				$47,955

7.3 RESULTS OF COST ANALYSIS

Table 7.1 summarizes the total HAVE system technology cost for a 750-cu. yd. batch to range from $82.10 per cu. yd. to $87.90 per cu. yd. for two different types of contaminated soils. It should be noted that the dollar total does not add up to the total cleanup cost because some cost categories that are site specific such as accessibility, availability of utilities, and local supervisory personnel were not included.

Further cost reduction may be feasible by treating larger volumes at a given site. Mobilization and startup costs can be reduced with two HAVE units on site. A project turnaround time of 18 days is required for 750 cu. yds. of contaminated soil as in Case 1. The same soil of 1,500-cu. yd. volume can be treated in a period of 33 days. Larger volumes of soil can be treated in multiples of 750-cu. yd. batches using two HAVE units. Thus, 3,000-cu. yd. and 9,000-cu. yd. soil volumes will require project durations of 2 months and 5 months, respectively.

8.0 RECOMMENDATIONS

The ex-situ thermal treatment technology demonstration conducted at the Hydrocarbon National Test Site was successful in remediating petroleum hydrocarbon contaminated soils to well below regulatory requirements. Four of the five demonstrations encountered some operational and equipment problems. Solutions to these problems resulted in the development of new ideas that were implemented in subsequent demonstrations. Some changes were also made in the demonstration schedule. These problems and solutions are discussed in the following sections.

8.1 PROJECT SCHEDULING

- The demonstration tests were designed assuming that the soil contaminants would be predominantly in the diesel oil range for Run 2, and diesel and heavy oil for Runs 3 and 4. However, the soils available during the demonstration period from the Naval Weapons Station, Seal Beach did not precisely meet these requirements. The Seal Beach soil contained significant amounts of lubricating oils and heavier petroleum fractions. As a result, and in part due to the inability to raise temperatures substantially to volatilize these heavier fractions, the project schedule was modified to increase the treatment duration, and the addition of another run. It is recommended that the contaminated soil be characterized well prior to or during the planning stages of implementations of this technology.

- The soils must also be characterized with respect to clay and moisture contents. These parameters will affect the treatment duration and temperature of operation.

- Late arrival of the equipment from another Vendor test facility delayed the start of operations at HNTS. In addition, system shutdown occurred due to wiring that came loose during transport of the equipment. These problems resulted in modifications being made to pre-ignition checklists to assure minimal shutdowns due to equipment failures.

8.2 PROCESS MONITORING

- The temperature monitoring data from the four levels in Cell No. 1 indicated that the number of temperature sensors in the monitoring system design was not sufficient to characterize the temperature distribution and heat transfer within the large soil pile. The number of temperature sensors was increased to better characterize the spatial temperature distribution. Sensors were also added to determine the injection duct to soil temperature gradients. The temperature monitoring frequency was increased to four per day.

- For Runs 3, 4, and 5, temperature sensors were also placed within the injection pipe wall at various levels. Soil temperatures at cell perimeter locations were measured for Runs 4 and 5.

- Temperature is one of the most important parameters determining treatment efficiency. For uniform and effective remediation within different sections of the soil pile, it is recommended that the soil temperatures be monitored at various longitudinal sections within each level of the soil pile, and also at perimeter locations within each level. Moreover, to adjust air flow rates to achieve desired temperature changes in different levels, it is recommended that the injection pipe temperatures be monitored at each level.

- Provisions should be made to monitor the temperature of the interstitial space between the soil pile and the membrane cover. This will provide information as to whether the injected air is bypassing the soil and short-circuiting into the vapor extraction ducts.

- Recommend a temperature monitoring scheme similar to that of Cell No. 4 as shown in Figure 4-15. The temperature monitoring layout should incorporate the recommendations described in the above two bullets.

- The monitoring of treatment progress was accomplished in the field by analyzing soil samples using thin layer chromatography (TLC). This is due to the long turnaround time for GC analysis of TPH from off-site laboratories. The results from Runs 3, 4, and 5 indicate a direct correlation between soil moisture content and the TPH concentration levels. Soil moisture can be measured quite rapidly and easily in the field using microwave-based moisture analyzers. Based on this information, air injection flow rates can be adjusted to reduce moisture and TPH levels at high concentration areas. It is recommended that field measurement of moisture be used as an additional tool to monitor treatment progress.

- Air flow monitoring is critical in process control to reduce or increase the temperature of the soil pile. During Run 4, system shutdown occurred due to a malfunctioning flow sensor. It is recommended that in addition to the sensor in the hot air flow duct (see process flow diagram, Section 4.4), additional backup sensors be provided in the injection manifold. Also, an air flow monitor should be located in the vapor plenum.

8.3 TREATMENT CELL DESIGN

- The demonstration Run 2 with mixed fuels contaminated soil indicated that the treatment cell design was not satisfactory in uniformly transferring the heat from the injected air to the contaminated soil. As a result, the interstitial vapor temperature between the soil pile and the membrane cover was substantially higher than the soil temperature. The design of the treatment cell was modified as a result for Runs 3, 4, and 5, as indicated in Section 4.1.2. In addition, aluminized fiberglass fabric was used for vapor seal for Runs 3 and 4.

- During demonstration Run 4, the aluminized fiberglass fabric delaminated due to high wind loads at the test site. Field tests were conducted using several different types of membrane materials, and heavyweight acrylic fiberglass was selected for the subsequent demonstrations. It is recommended that this fabric, or better materials that can withstand the high interstitial vapor temperatures and high wind loads, be used in any implementations of this technology.

- The treatment cell design was further modified for Runs 4 and 5 to achieve uniform soil temperatures during operation. This was accomplished by reducing the soil depth between injection levels to 18 inches. For soils contaminated with substantial amounts of petroleum fractions in the high boiling range, it would be desirable to limit the depth between injection levels to 18 inches to achieve rapid and uniform heating at all levels.

8.4 HAVE SYSTEM OPERATION

- Soils contaminated with volatile petroleum hydrocarbons can be remediated at low temperatures as in Run 1. However, depending on the contaminant concentration, somewhat higher temperatures may be used for faster remediation.

- HAVE system operating parameters used in Run 5 provided smooth operation and effective remediation. These values are recommended for the treatment of soils with low clay content. For soils with high clay content, a similar operating procedure may be adopted, except that temperatures may need to be raised somewhat higher as in Run 4 during the latter portion of treatment when moisture levels are low.

- It is recommended that success of the operation be measured by analyzing for soil hydrocarbon concentration according to the following carbon ranges: C8 to C13, C14 to C18, C19 to C22, C23 to C30, and C30+. The analytical costs involved are marginal, and since the treatment rates are different for the different fractions, this will provide useful information for future remediations.

9.0 CONCLUSIONS

Conclusions presented in this section cover not only the cost and performance of HAVE technology, but also the parameters which control the success of the HAVE technology. These parameters are then translated in the applicability of this technology to other contamination problems at other sites.

9.1 COST AND PERFORMANCE

The application of HAVE technology to contaminated soils resulted in petroleum hydrocarbon removals of 97 percent and 95 percent during demonstrations conducted at the Hydrocarbon National Test Facility at Port Hueneme, California. The treatment objective was 100 ppm for gasoline, 250 ppm for diesel and heavy oils, and 1,000 ppm for heavier fractions (C23+). The treatment objective for diesel and heavy oil fractions (C14 to C22) was exceeded by 80 percent, with the final concentrations from the two runs averaging at 59 ppm. The average final concentration for the heavier fractions (C23+) was 126 ppm, and the treatment objective in this case was exceeded by 88 percent. Gasoline components were not detected in the treated soil.

The average throughput rate for Test Nos. 4 and 5 is 1.6 cu. yds. per hour. The cost for implementation of this technology to treat 750-cu. yd. batches of soil are estimated to range from \$82 per cu. yd. to \$88 per cu. yd. In addition to the cost and technical performance, the demonstration results suggest the following additional conclusions:

- The HAVE system effectively removed a range of petroleum hydrocarbons from the low boiling to the high boiling range from contaminated soils. The average removal efficiency for C4 to C22 hydrocarbon fraction was 98 percent, and the removal efficiency for C23+ fraction was 95 percent. These data are from the last two demonstration runs for remediation of mixed fuel contaminated soils.

- The HAVE system components are easily transported on tractor/trailer rigs. Assembly of the equipment and construction of the treatment cell is normally accomplished in 3 days. Dismantling and removal of equipment takes about 3 days.

- Site preparations for the demonstrations were minimal as improvements were already made to the site as part of the HNTS test program. A prepared staging area or concrete pad would be suitable for remediating multiple batches of contaminated soils. A graded surface free of rocks and sharp objects that can damage the liner material may be satisfactory for treatment of small soil volumes. The area should be graded to a 1 to 2 percent slope, and storm water must be directed away from the treatment system.

- The technology requires an area approximately 150 feet by 80 feet for constructing a 750-cu. yd. treatment cell and setting up the HAVE equipment.

- Electric power consisting of 40-amp 220-volt service must be available for most units. Alternately, electric power could be supplied by an on-site mobile generator. A natural gas supply must be available for operating the furnace and catalytic oxidation units. Propane can be used instead of natural gas with somewhat higher fuel costs. Phone services were required on-site to coordinate demonstration activities.

- The primary factors that affect process throughput are soil characteristics, contaminant type, concentration and distribution, and moisture content of the soil. These factors in turn affect the treatment duration.

- The demonstration runs indicate that the HAVE technology performs well with soils containing less than about 14 percent moisture, and less than 20 percent clay. The soil TPH concentration of 5,000 ppm was used for cost estimates in this report. Soils with higher hydrocarbon concentrations can be remediated if the treatment period is extended. The presence of clumps with hydrocarbons in the C23 to asphalt range will reduce the treatment efficiency.

- Low temperature operation (132°F to 150°F) was successful in remediating soils contaminated with gasoline constituents. Low temperature operation was not satisfactory for the remediation of soils contaminated with semi-volatile and non-volatile petroleum fractions using the original HAVE system configuration.

- The modified HAVE system was able attain average soil temperatures at the end of treatment ranging from 310°F to 410°F. The enhanced design allowed remediation of contaminated soils to below target levels as noted above.

- This technology can be applied without any major soil pre-processing requirements.

- The HAVE system performed at 75 percent efficiency. Downtime was due to unforeseen operation disruption such as melting of treatment cell membrane cover, repair of mobile power generator, and burner.

- Low temperature operation may result in condensate water collecting at membrane surfaces and draining to the soil perimeter. This water must be collected, treated to meet any local regulatory requirements, and disposed. For high temperature operation, any condensate collected during startup can be reinjected into the soil pile. Fugitive emissions were monitored during the demonstrations, and were found to be below regulatory limits.

- The HAVE system will generate air emissions from thermal destruction of the petroleum hydrocarbons in the soil. The catalytic oxidation system and pollutant monitoring devices must be maintained in good working condition to assure compliance with regulatory requirements for air emissions.

- Thermal treatment will alter the soil properties somewhat by reducing the moisture content, and removing or baking some plant and humic material in the soil. This does not prevent the future use of this soil as fill dirt or landfill cover.

- This technology can be readily adopted for full-scale implementation. Treatment costs will vary depending upon the project size. The unit treatment cost for 750 cu. yds. of soil is in the range of $82 to $88 per cu. yd. Larger volumes of soil can be treated at lower unit costs due to the reduction in mobilization, site preparation, and startup costs.

10.0 REFERENCES

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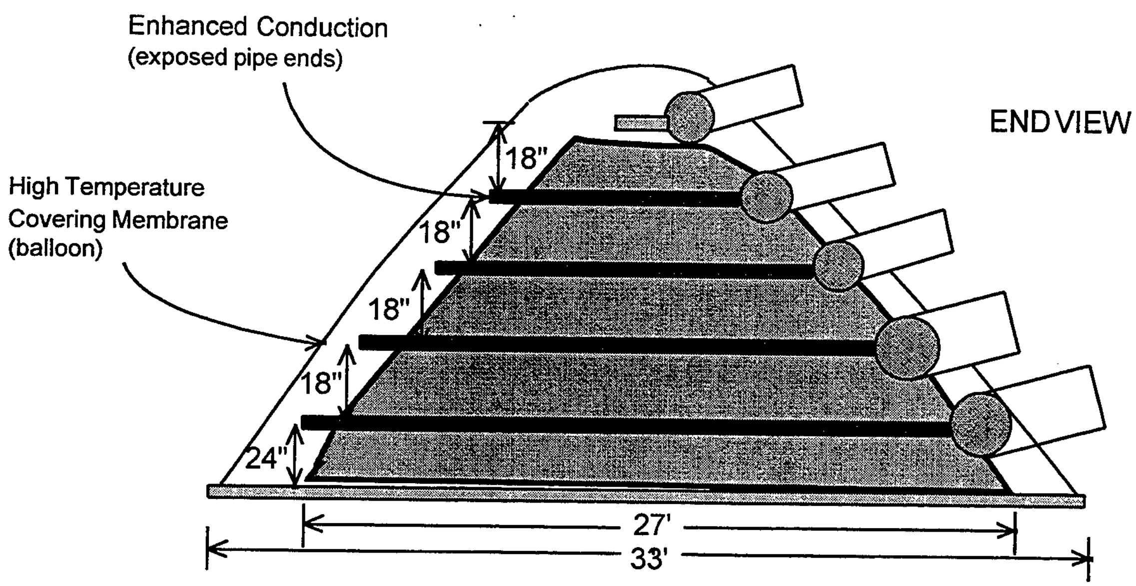
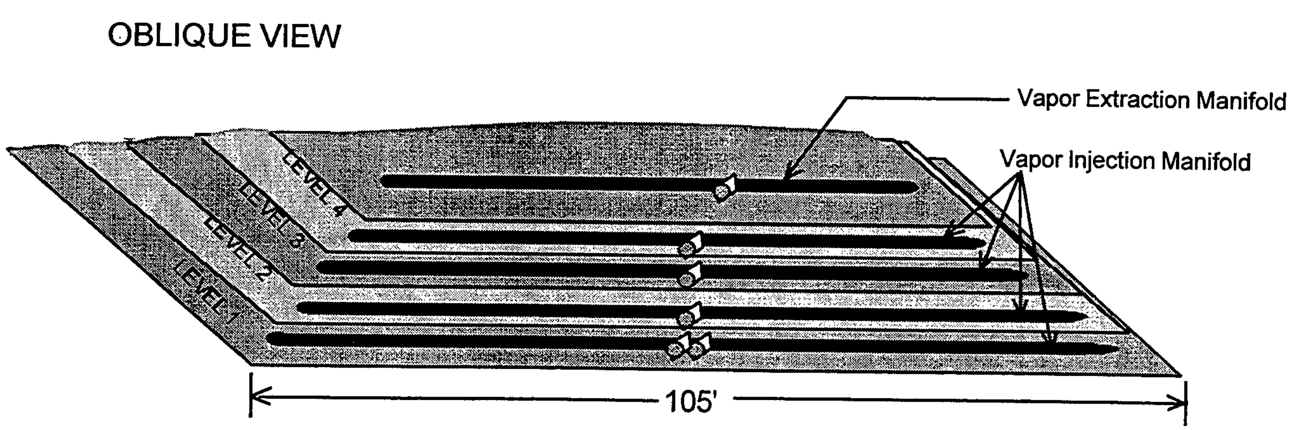
APPENDIX

TREATMENT CELL CONFIGURATIONS

TREATMENT CELL CONFIGURATION

Treatment Cell No. 5 - Mixed Fuel Soil Pile





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